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(54) PERCEPTION AND FITTING FOR A STAIR TRACKER

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(57)

ABSTRACT

A method for perception and fitting for a stair tracker includes receiving sensor data for a robot adjacent to a staircase. For each stair of the staircase, the method includes detecting, at a first time step, an edge of a respective stair of the staircase based on the sensor data. The method also includes determining whether the detected edge is a most likely step edge candidate by comparing the detected edge from the first time step to an alternative detected edge at a second time step, the second time step occurring after the first time step. When the detected edge is the most likely step edge candidate, the method includes defining, by the data processing hardware, a height of the respective stair based on sensor data height about the detected edge. The method also includes generating a staircase model including stairs with respective edges at the respective defined heights.

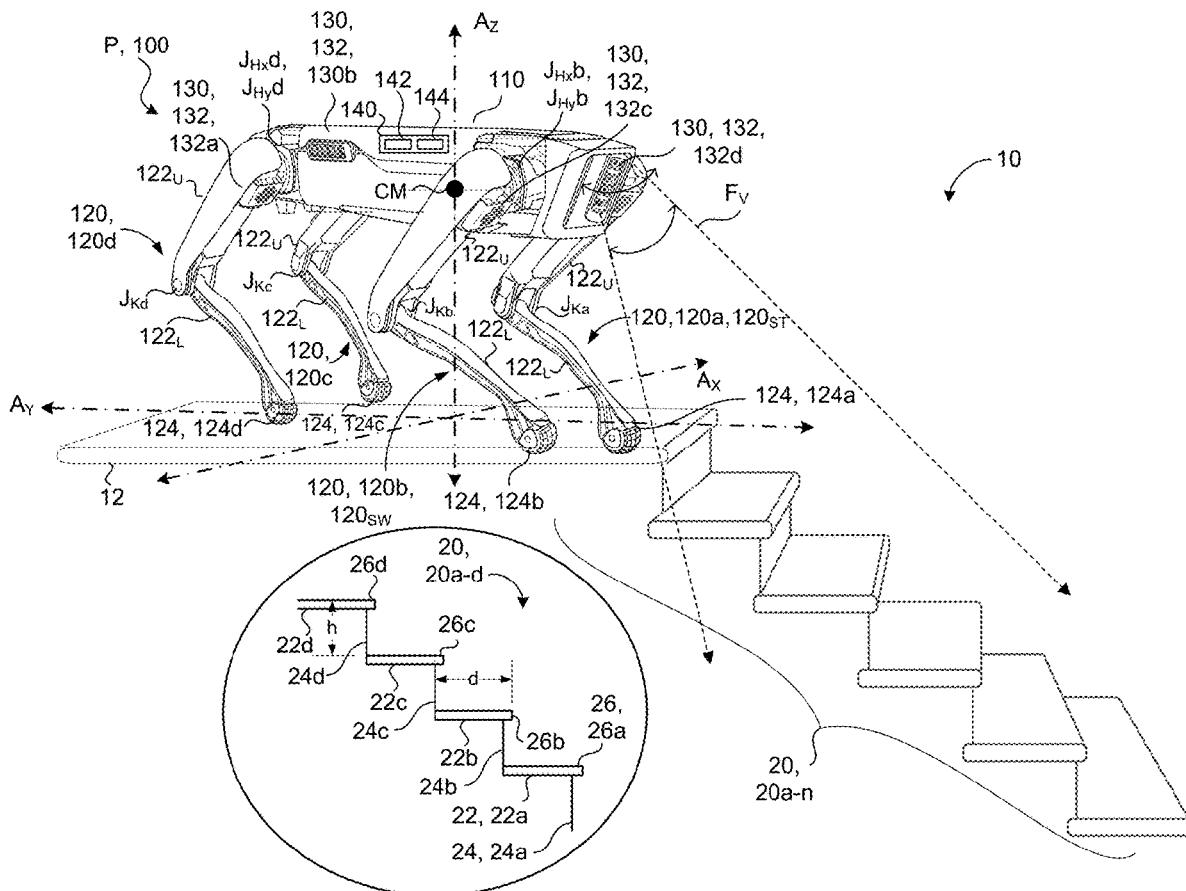
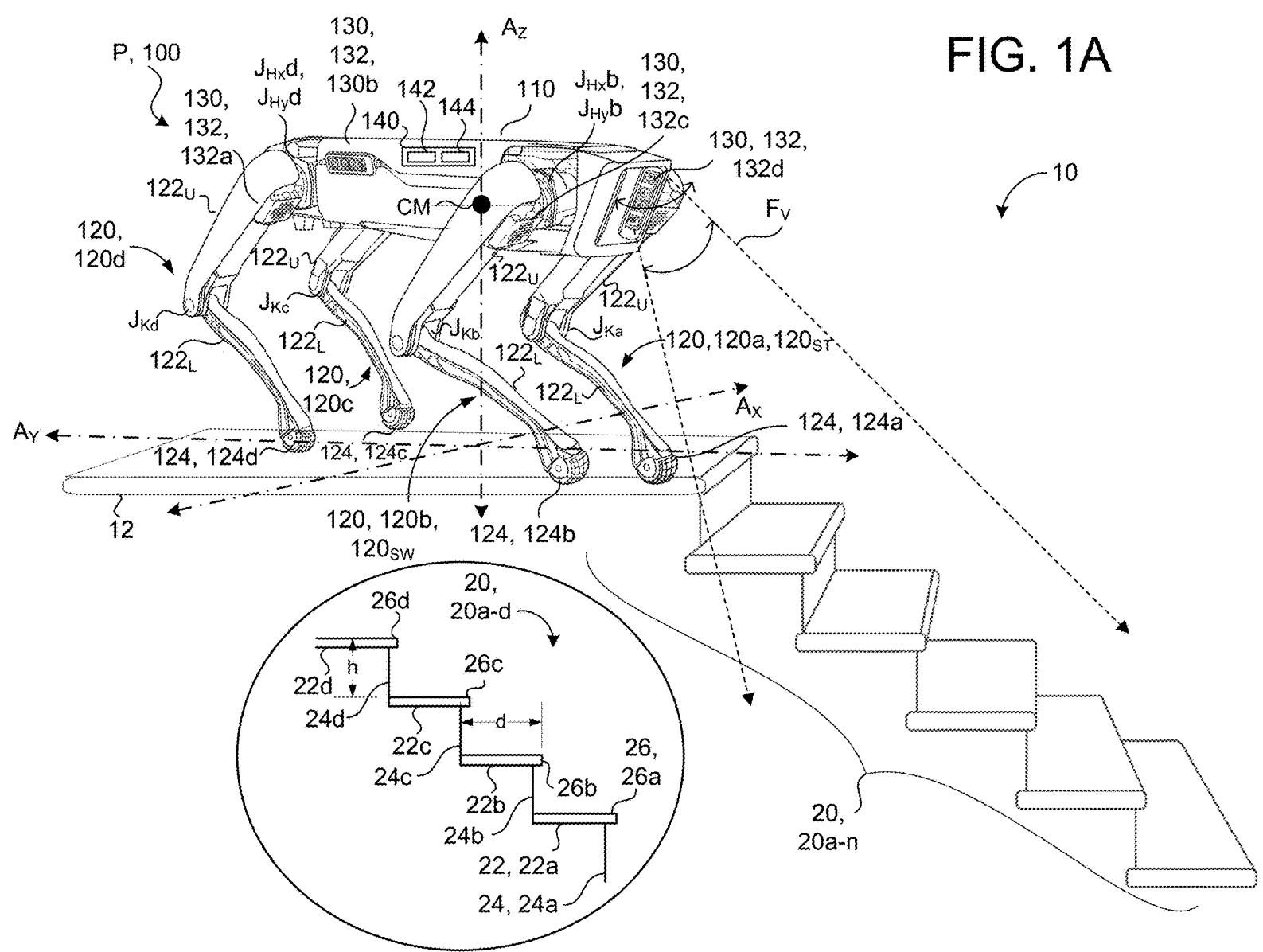


FIG. 1A



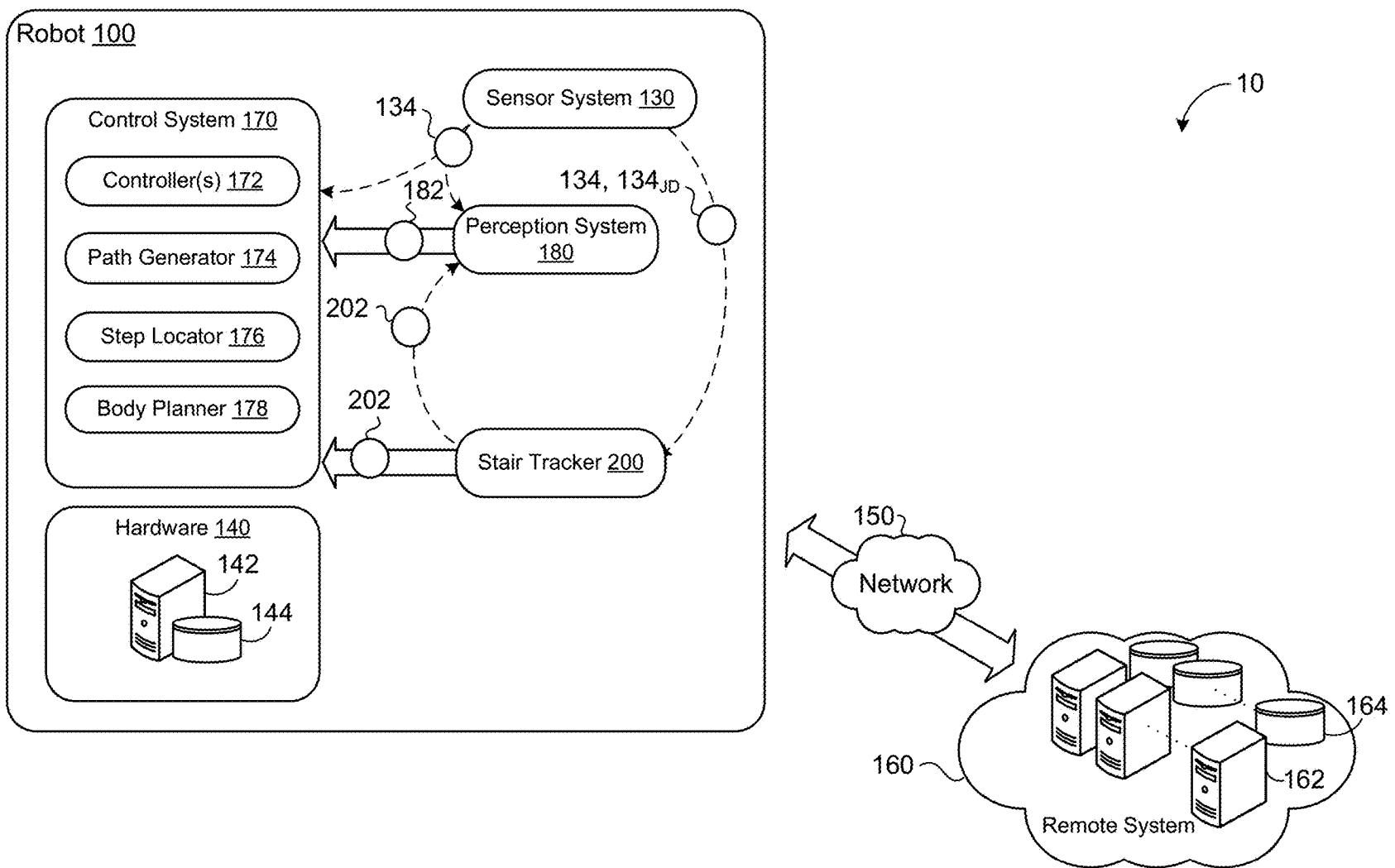


FIG. 1B

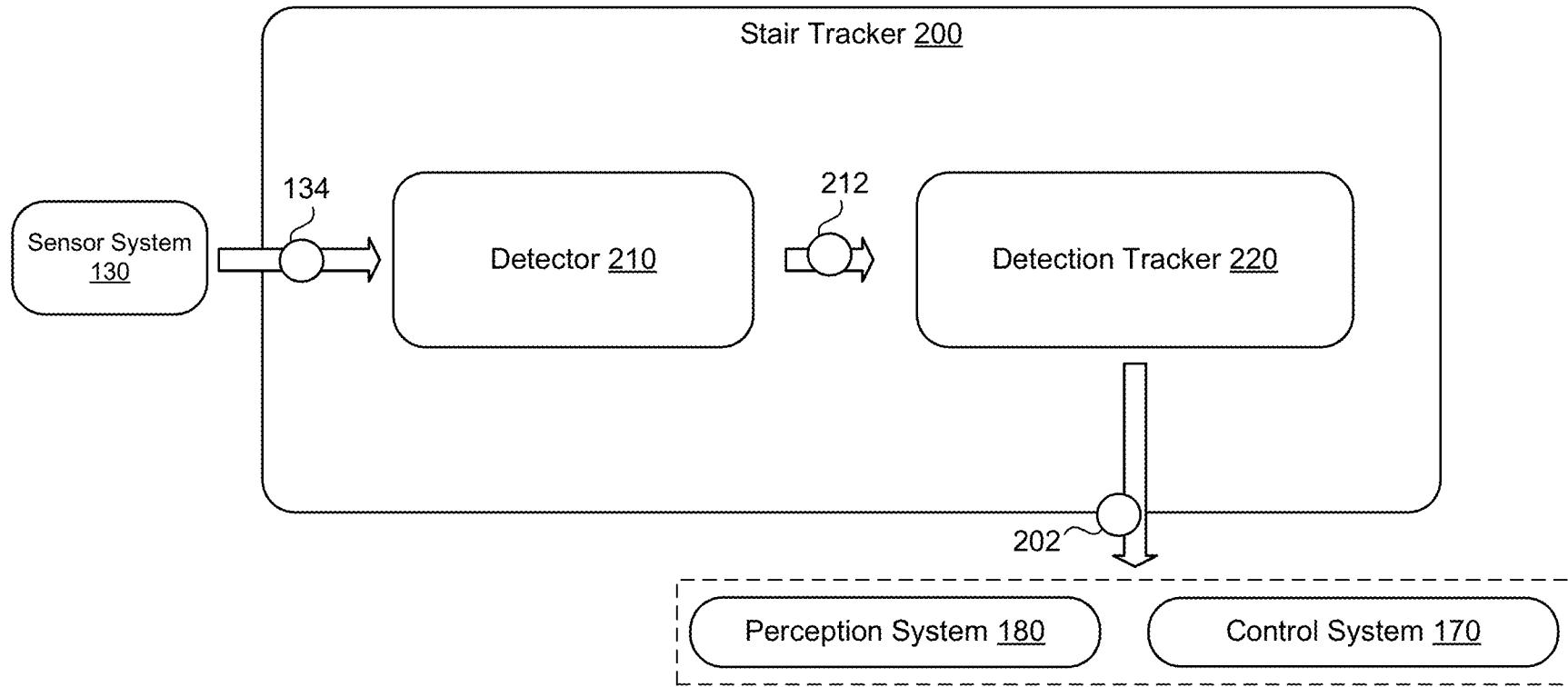


FIG. 2A

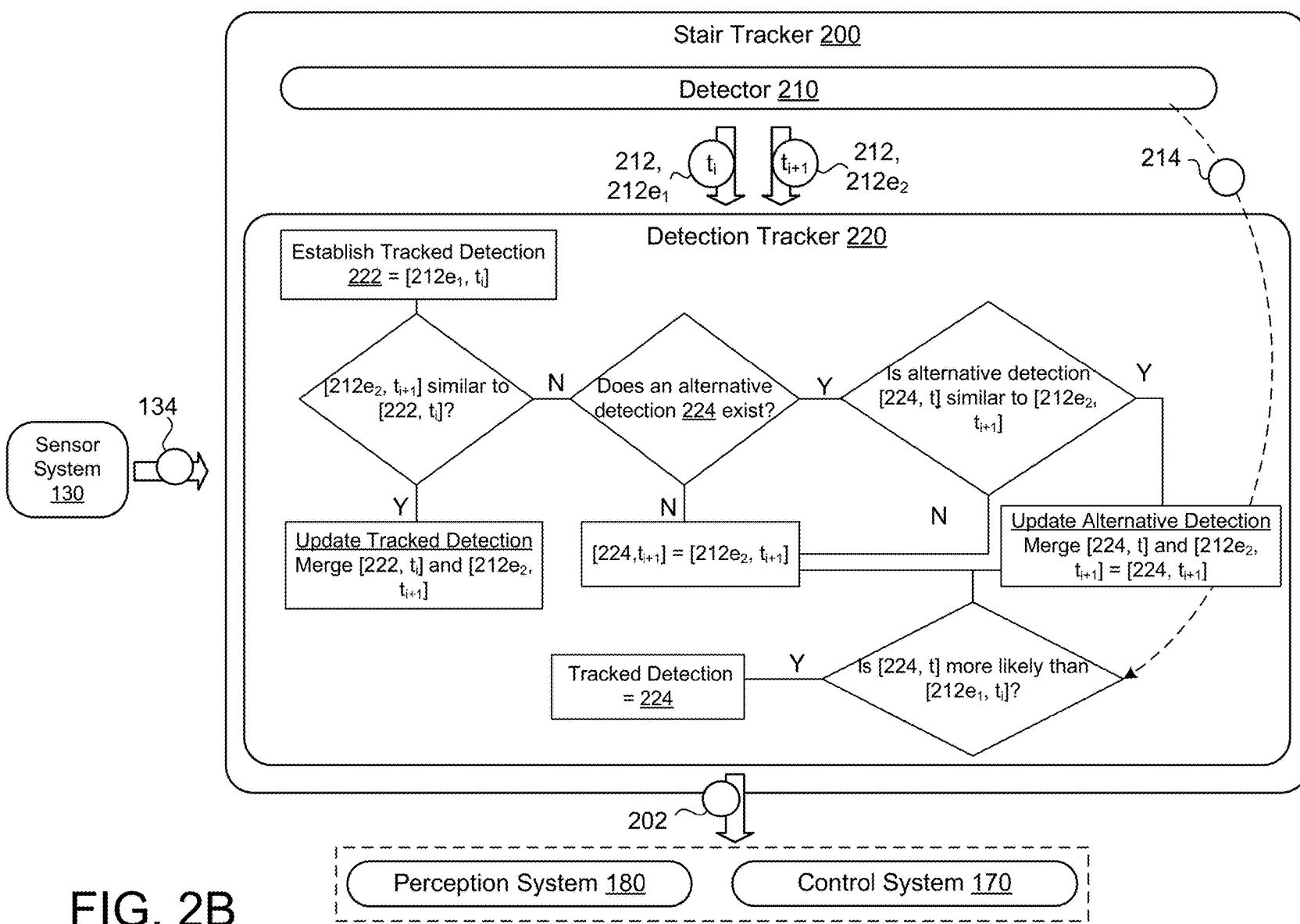


FIG. 2B

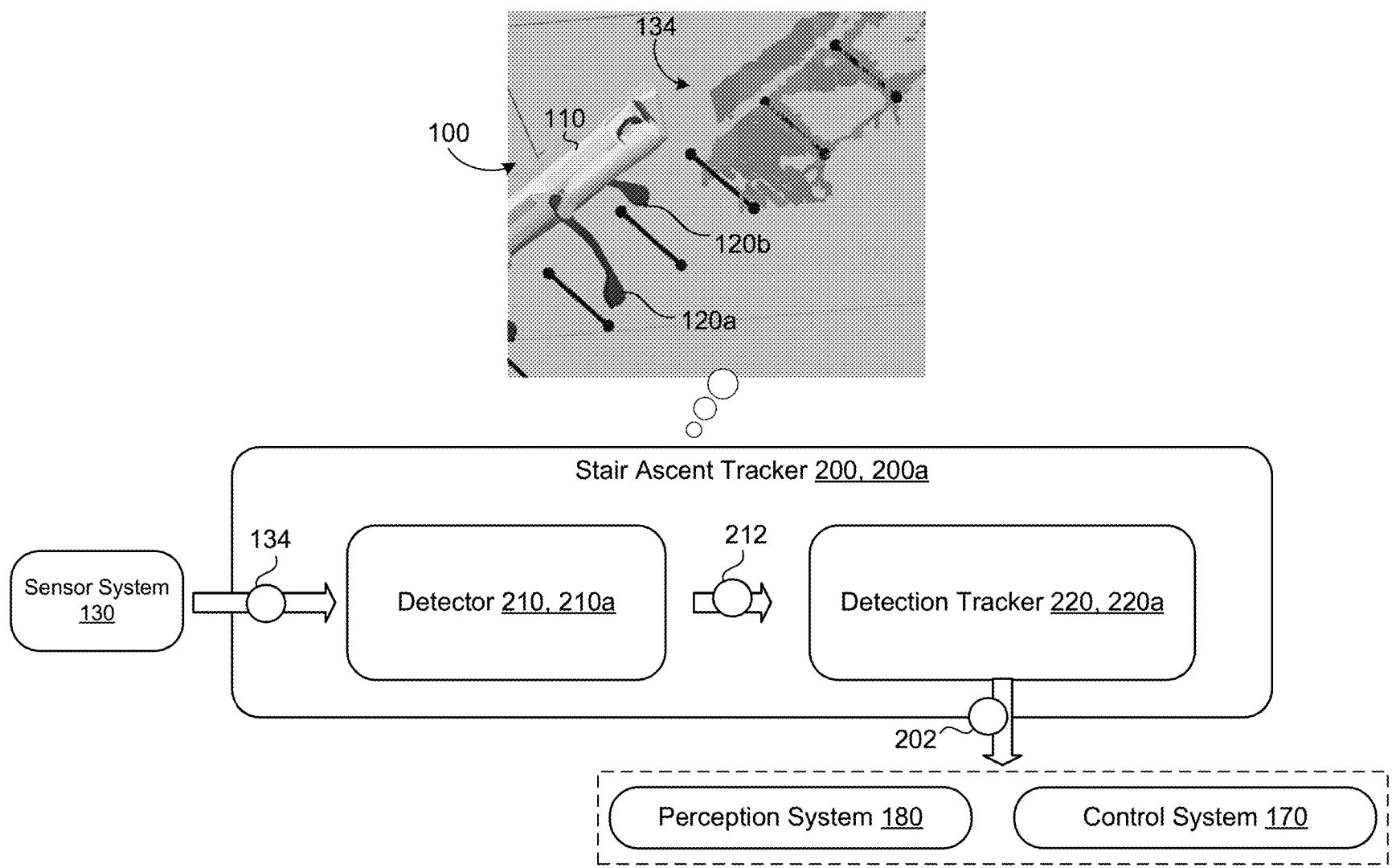


FIG. 2C

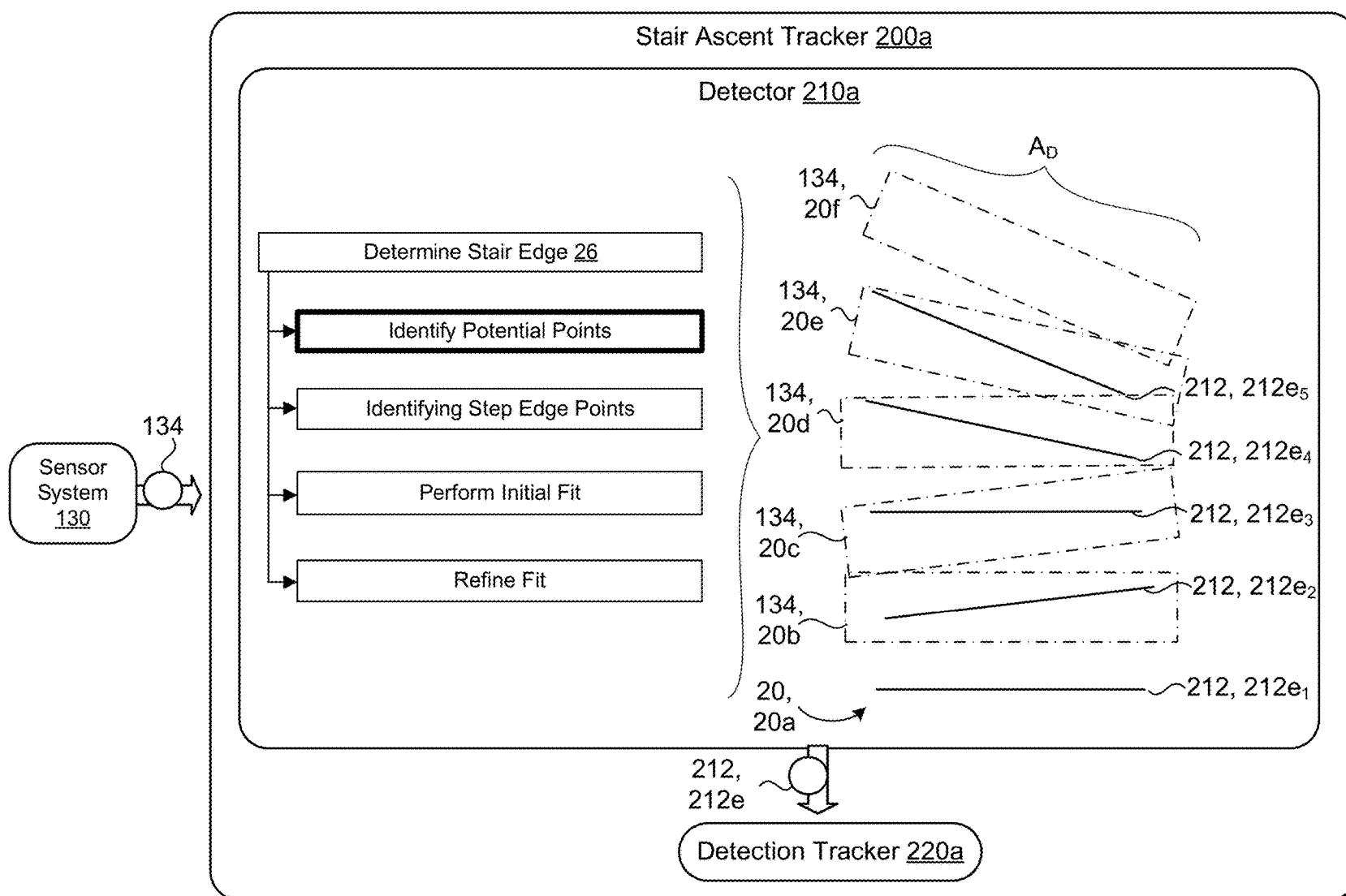


FIG. 2D

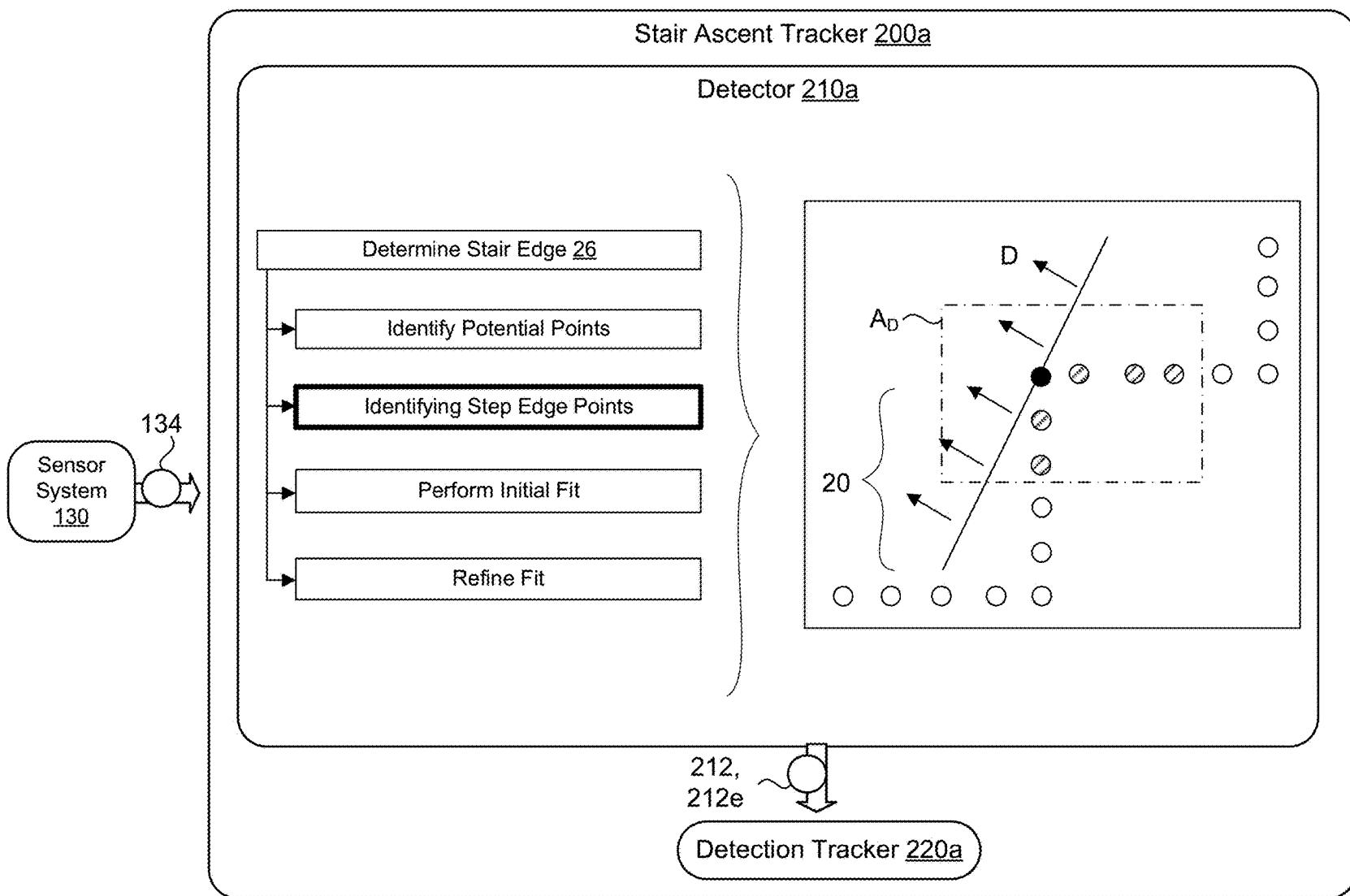


FIG. 2E

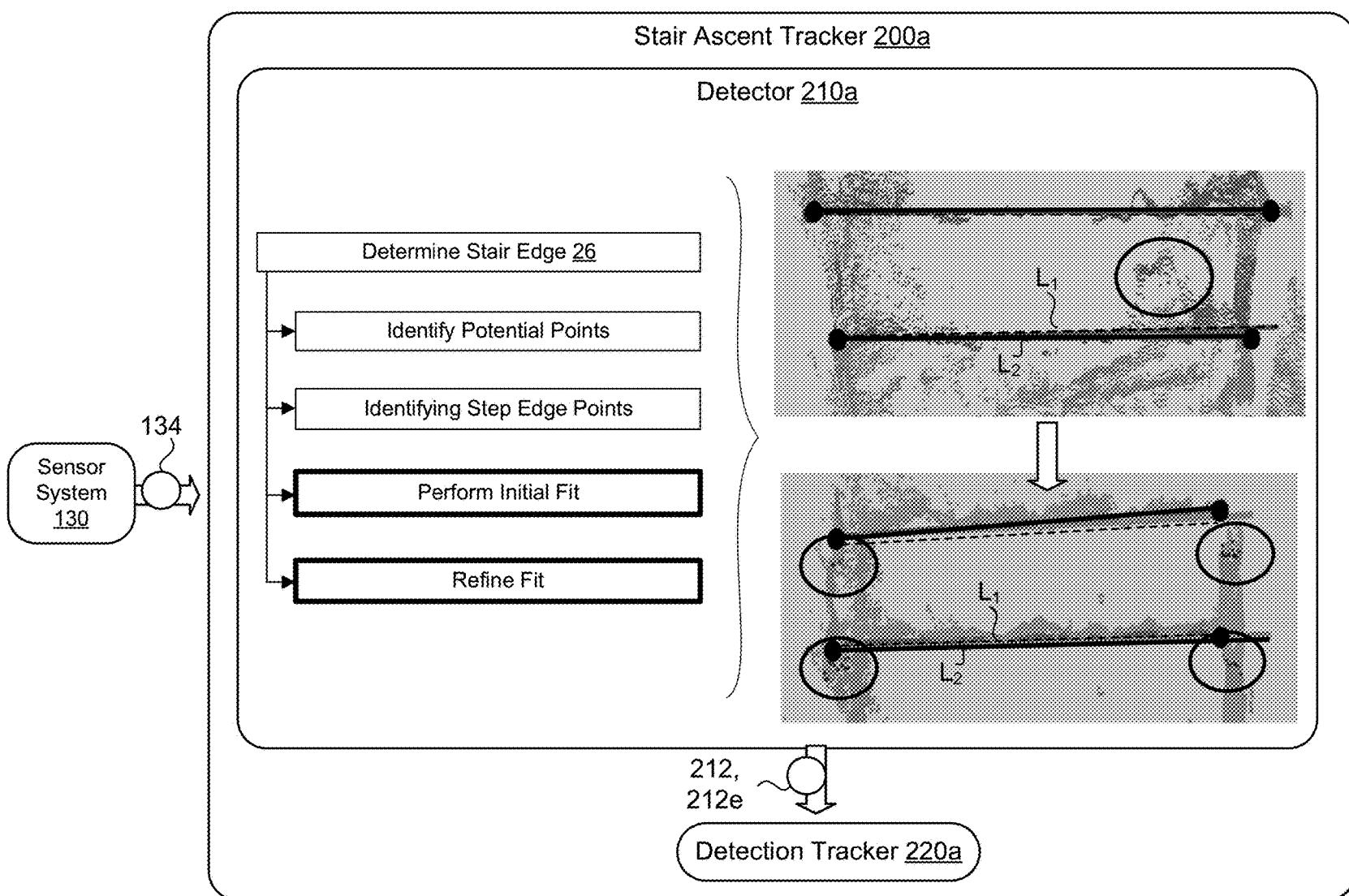


FIG. 2F

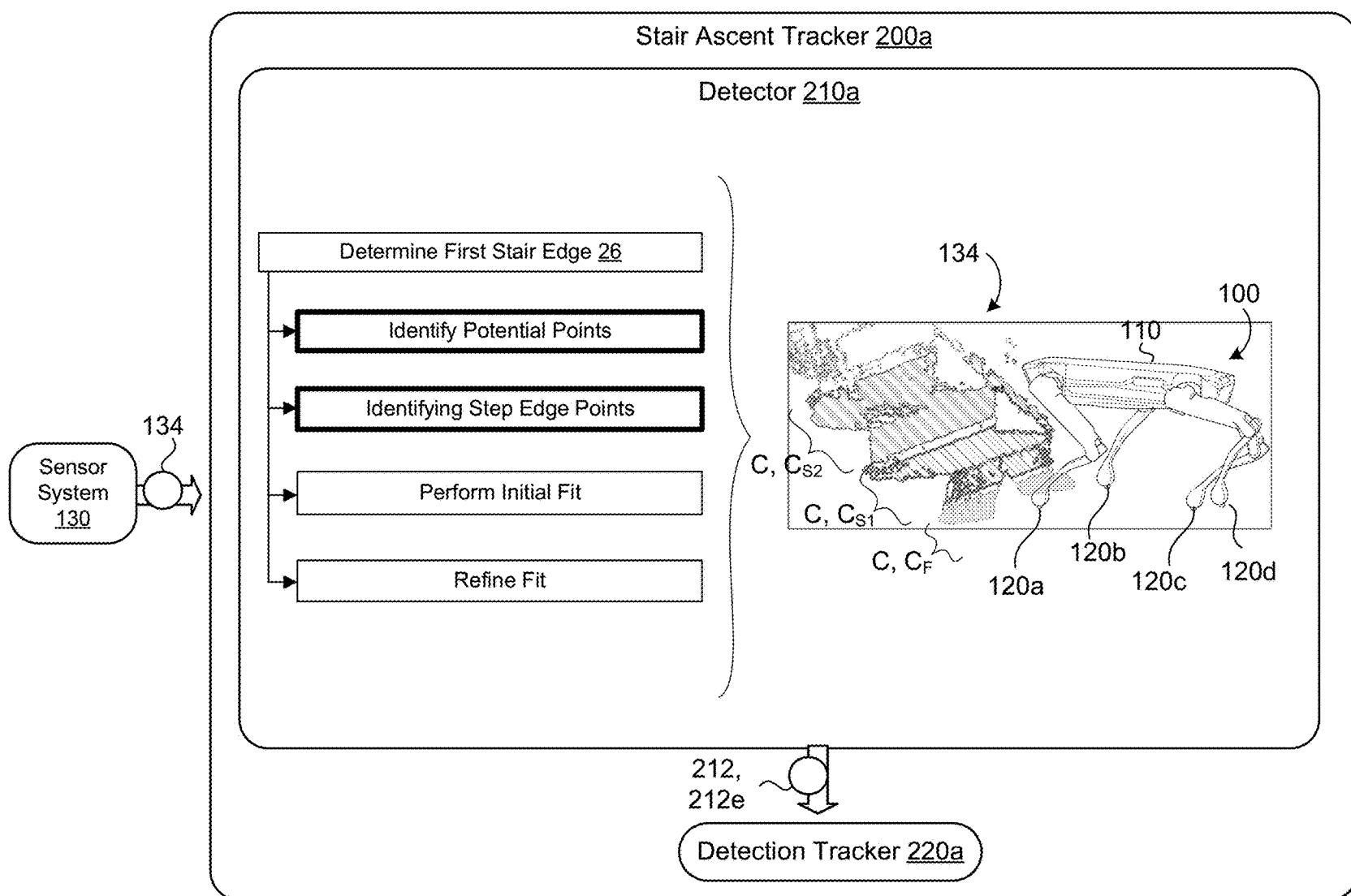


FIG. 2G

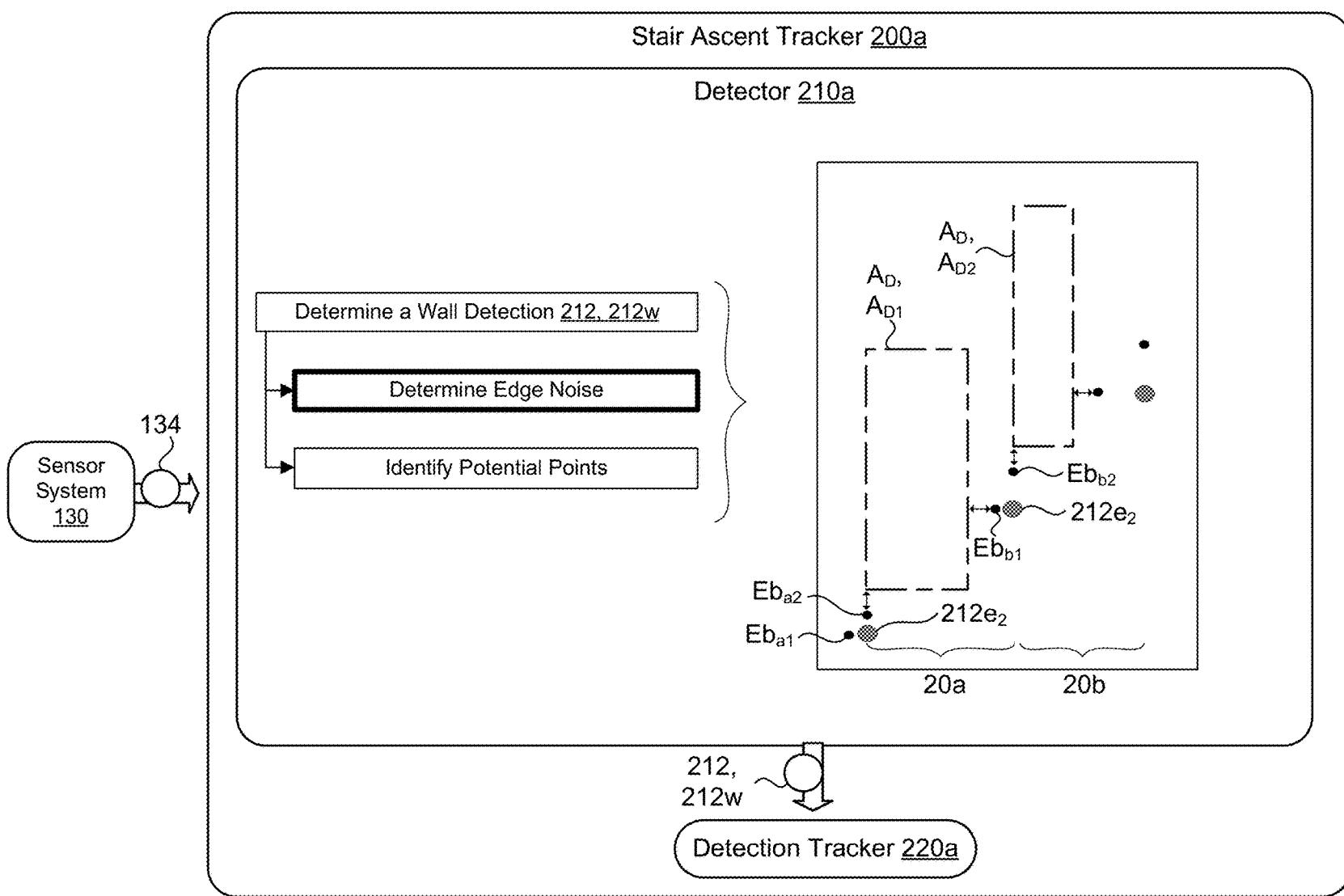


FIG. 2H

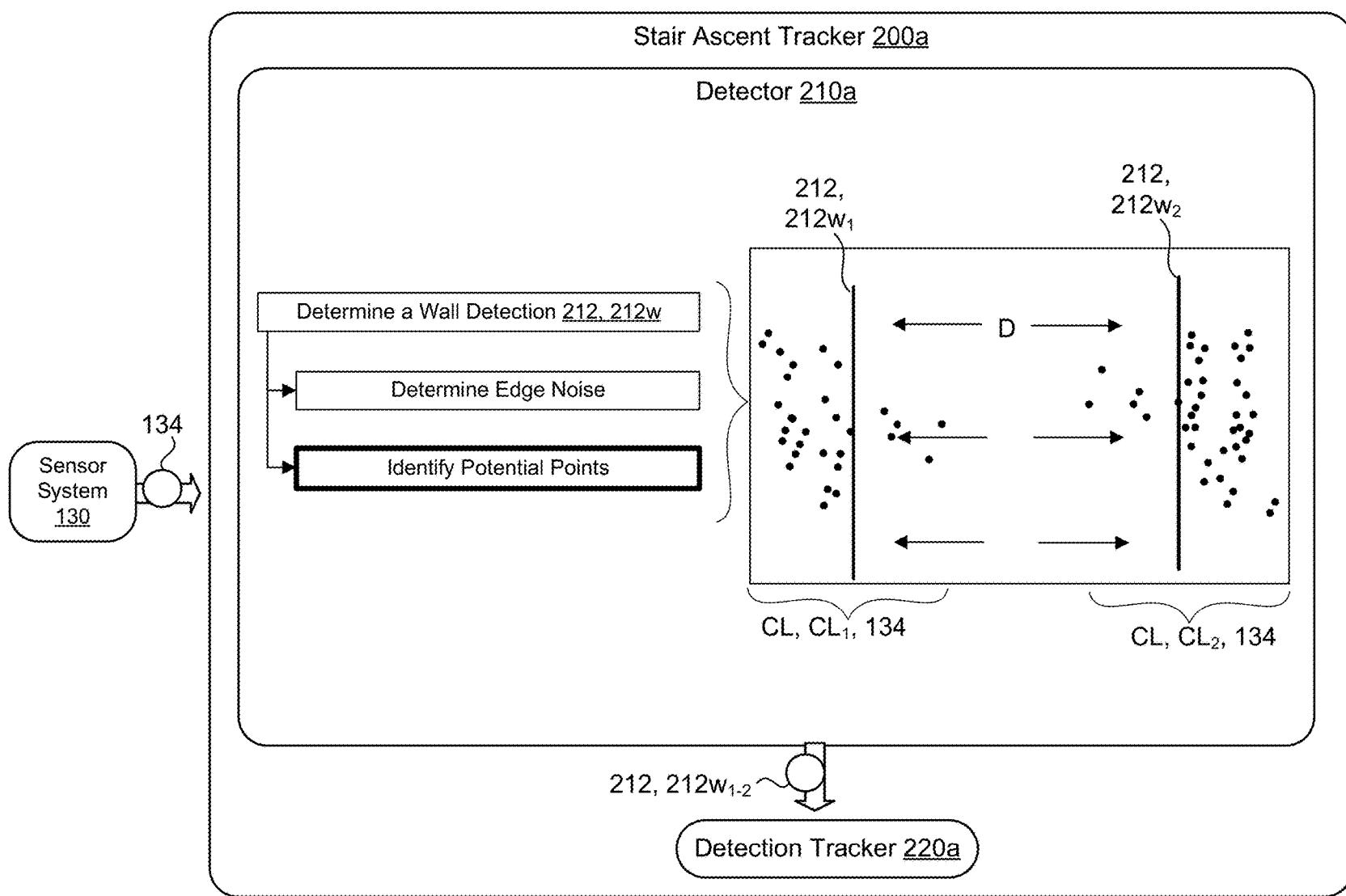


FIG. 21

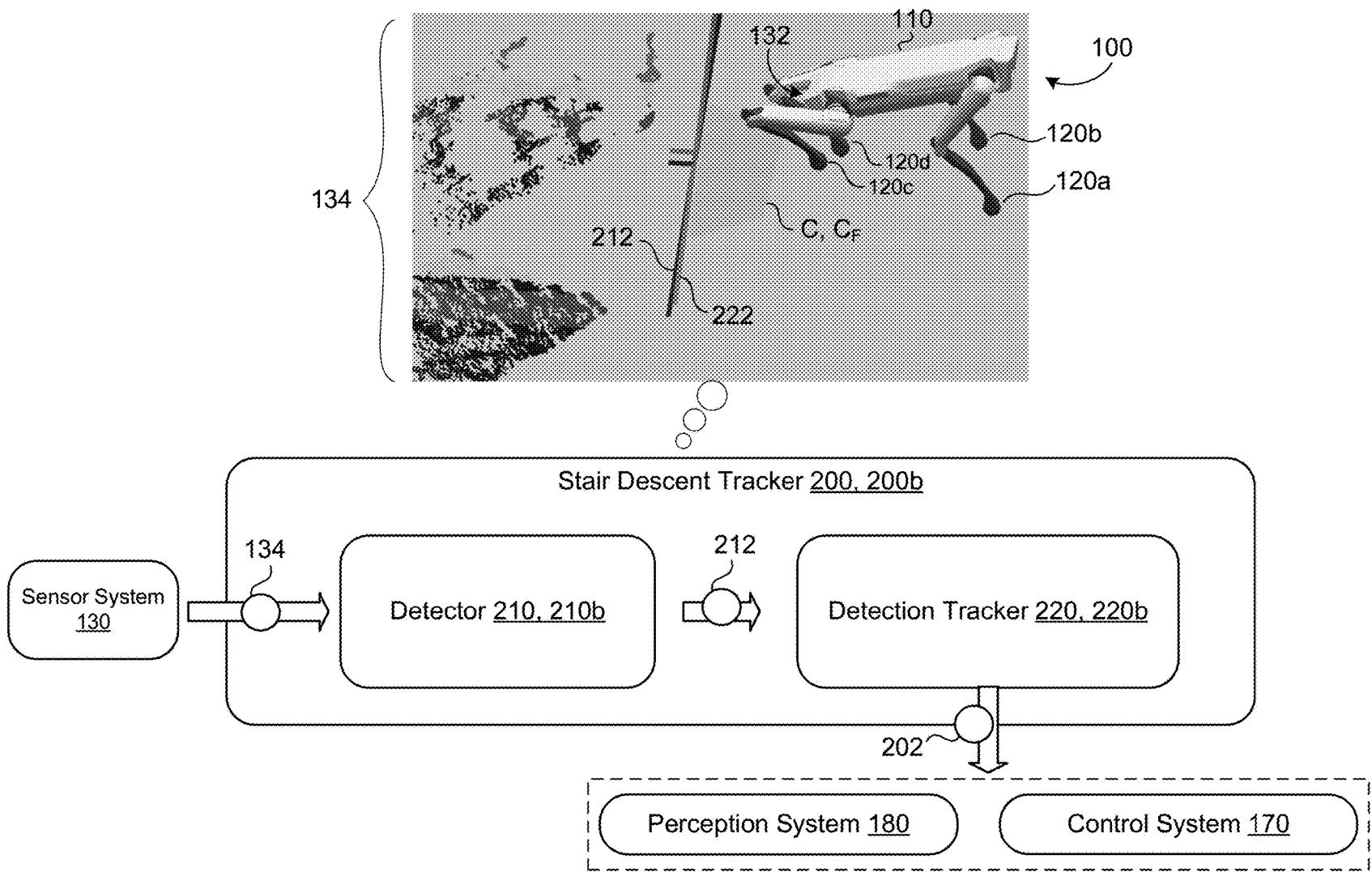


FIG. 2J

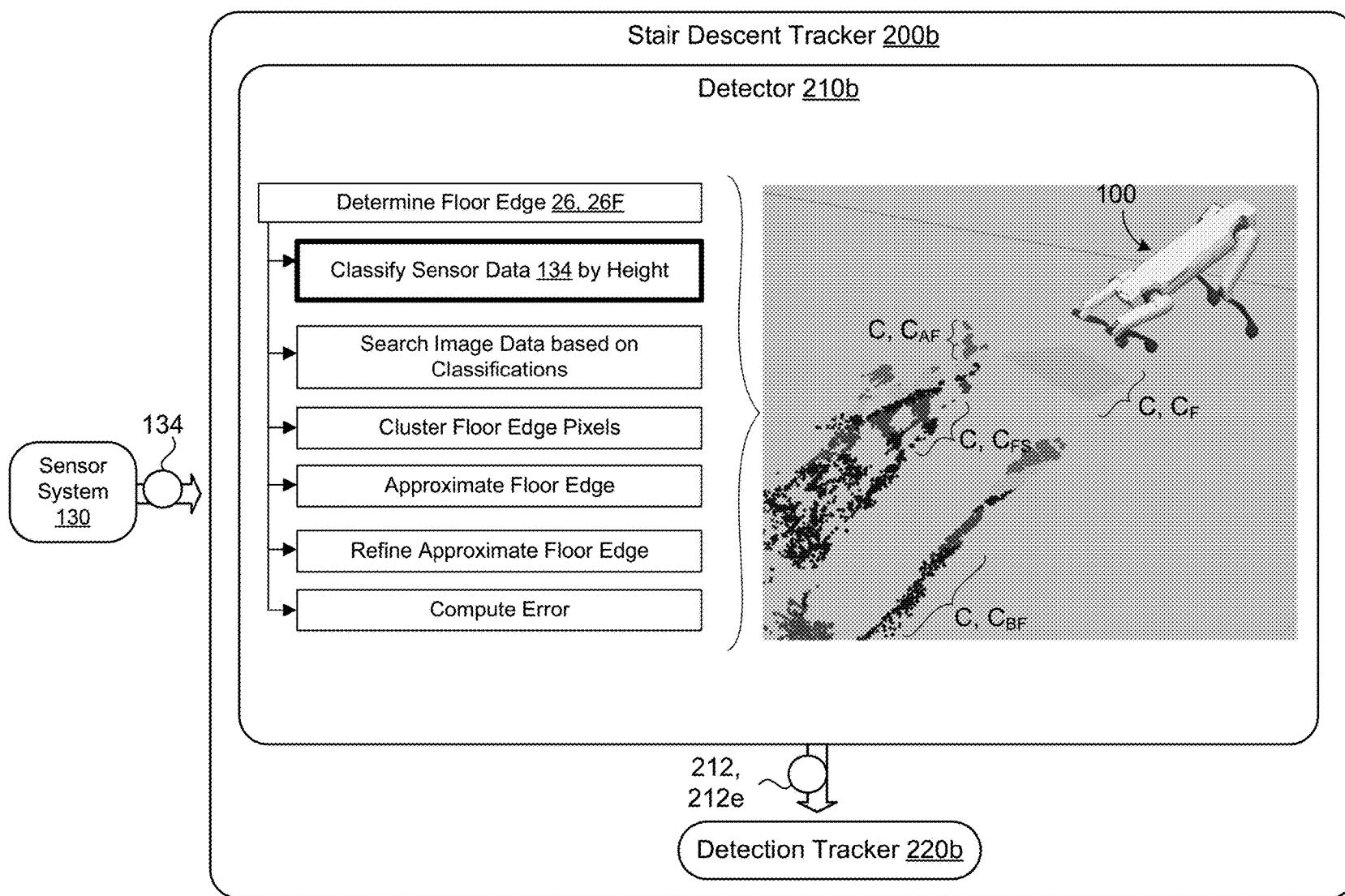


FIG. 2K

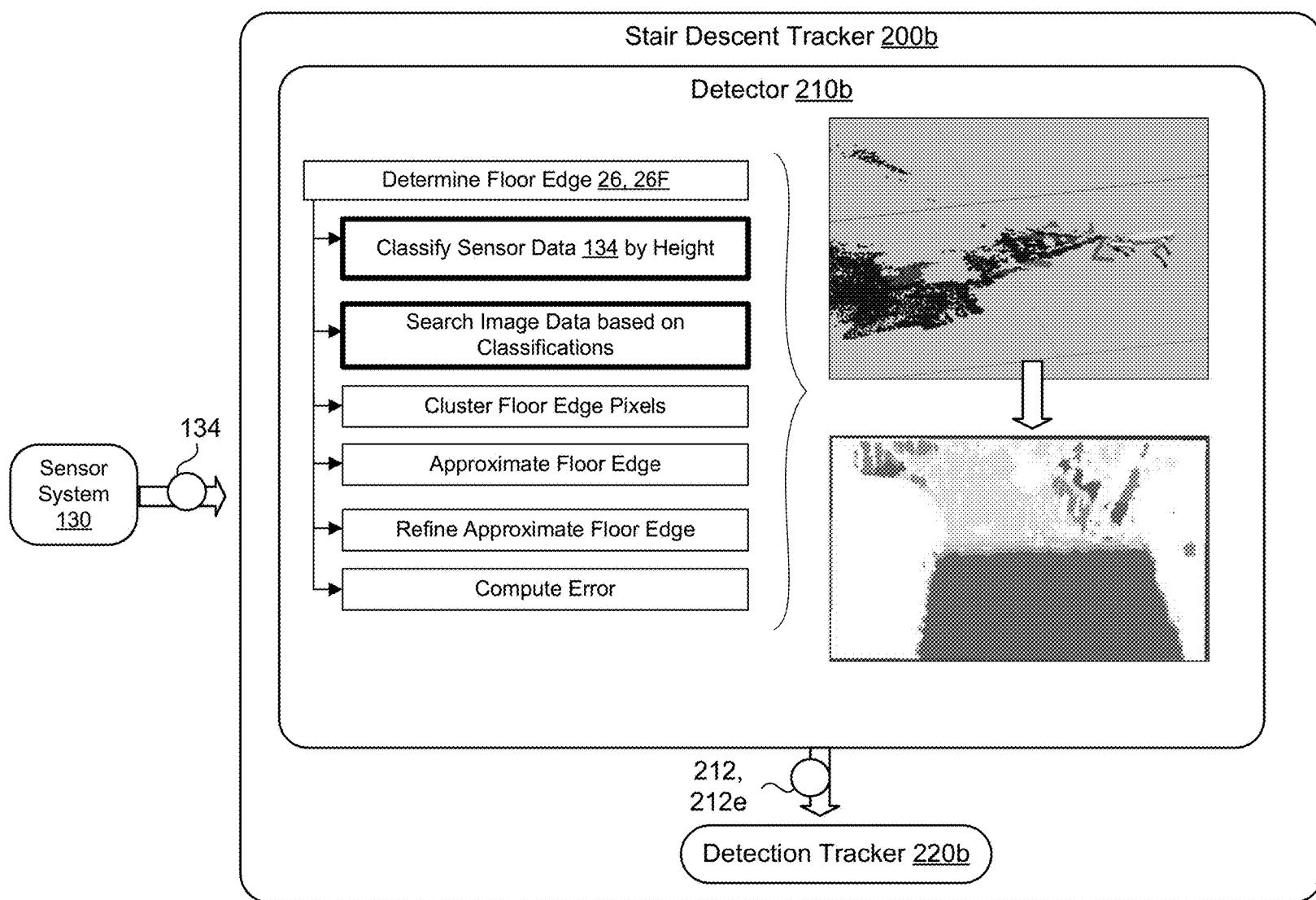


FIG. 2L

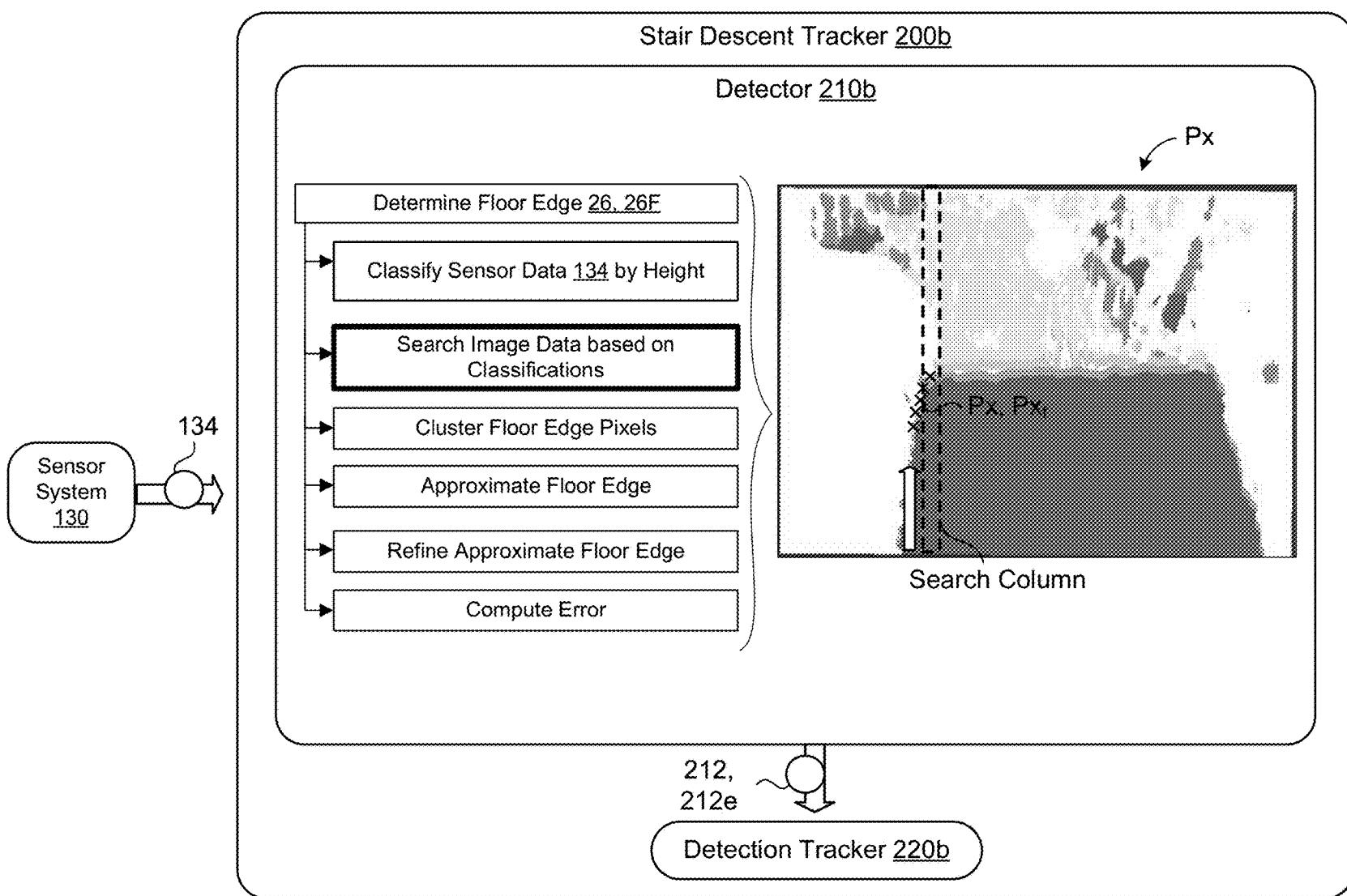


FIG. 2M

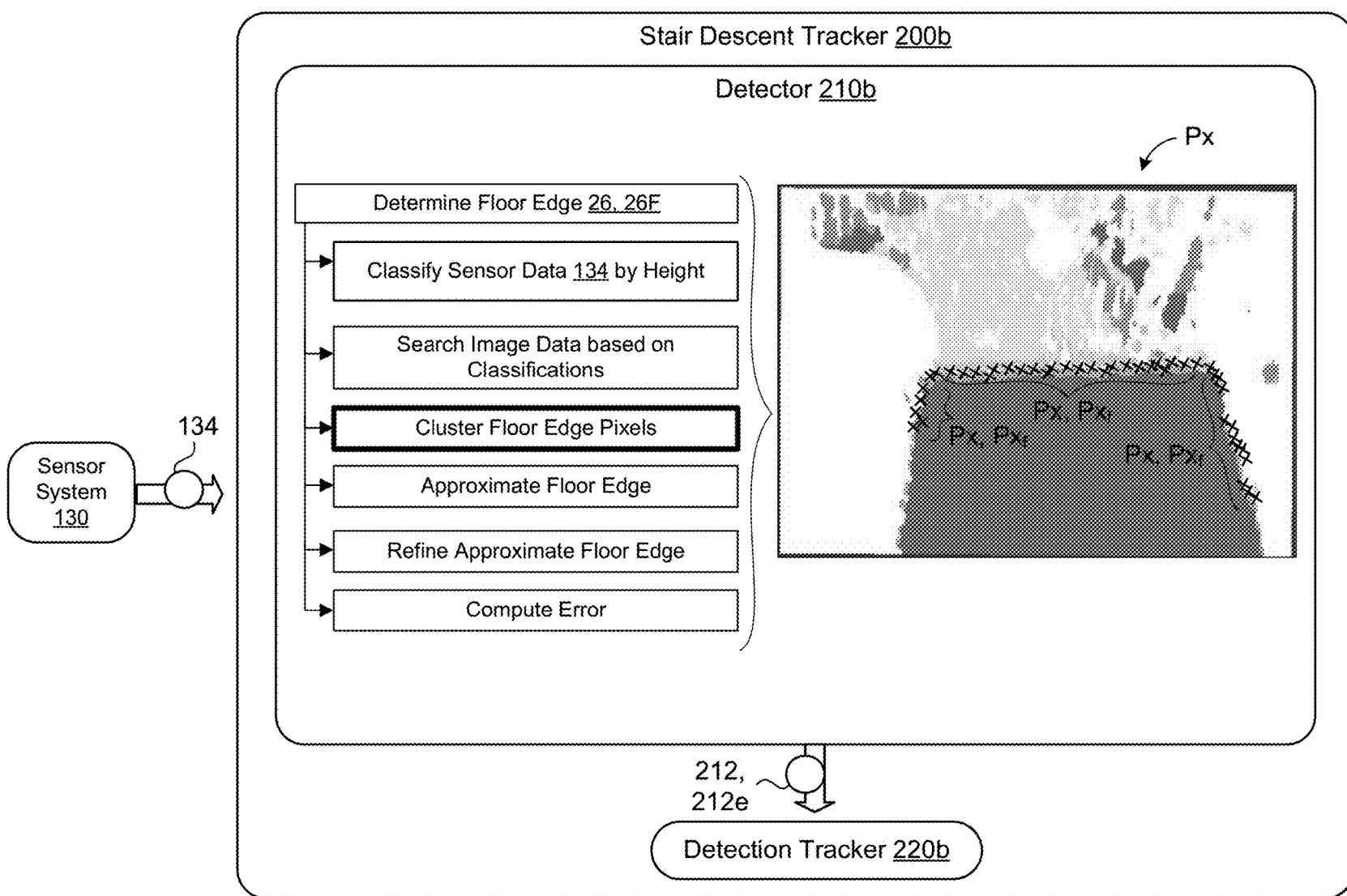


FIG. 2N

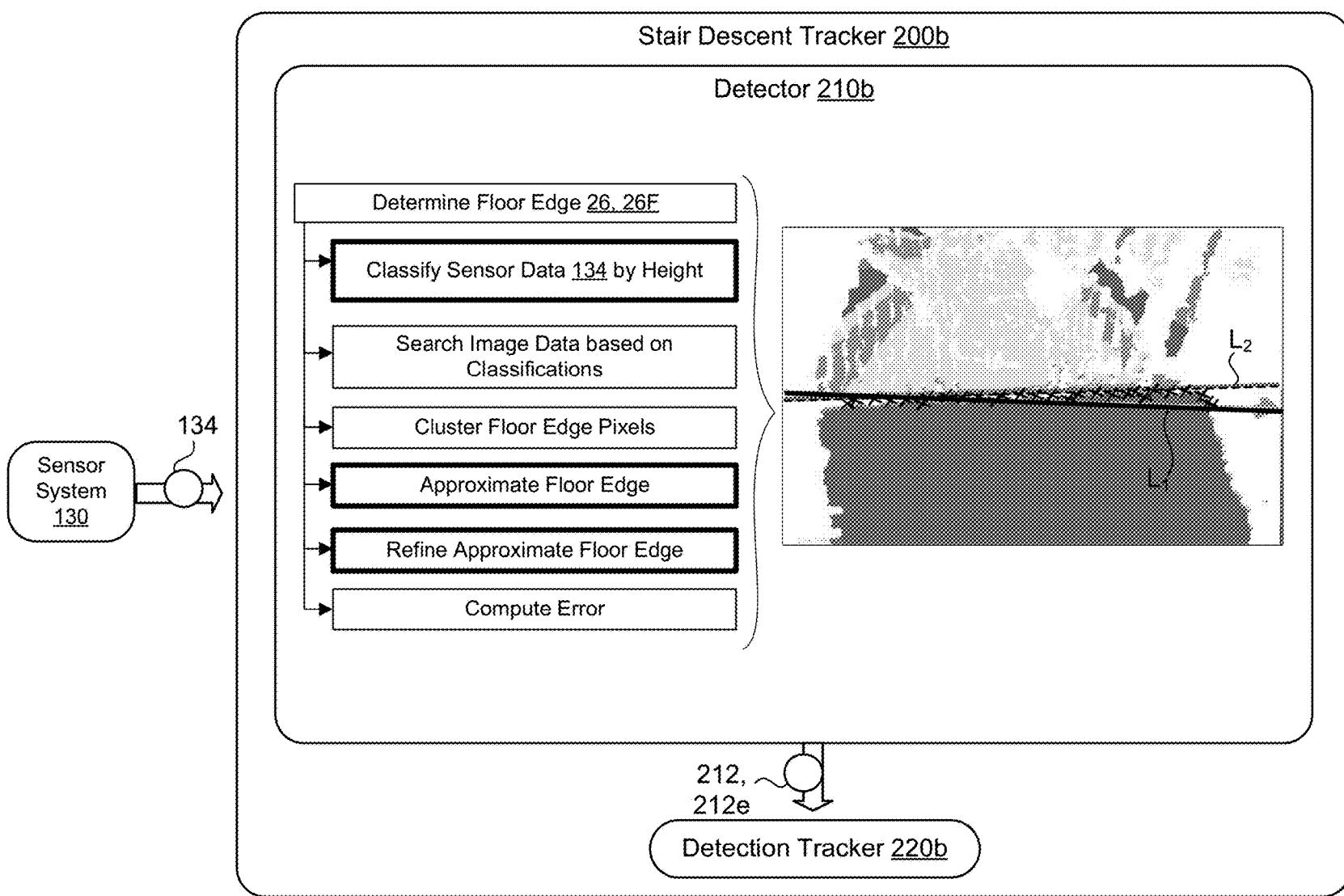


FIG. 20

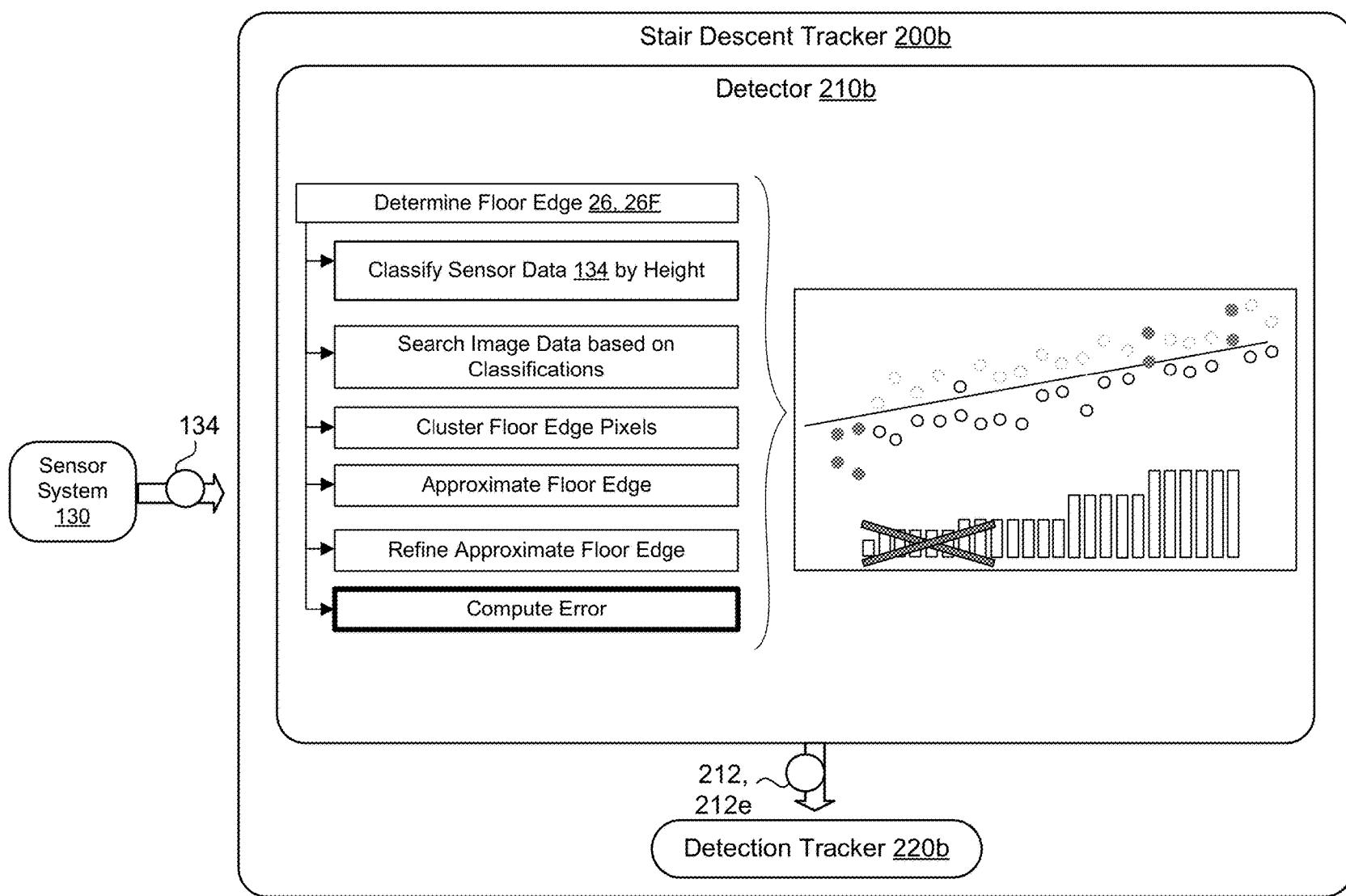


FIG. 2P

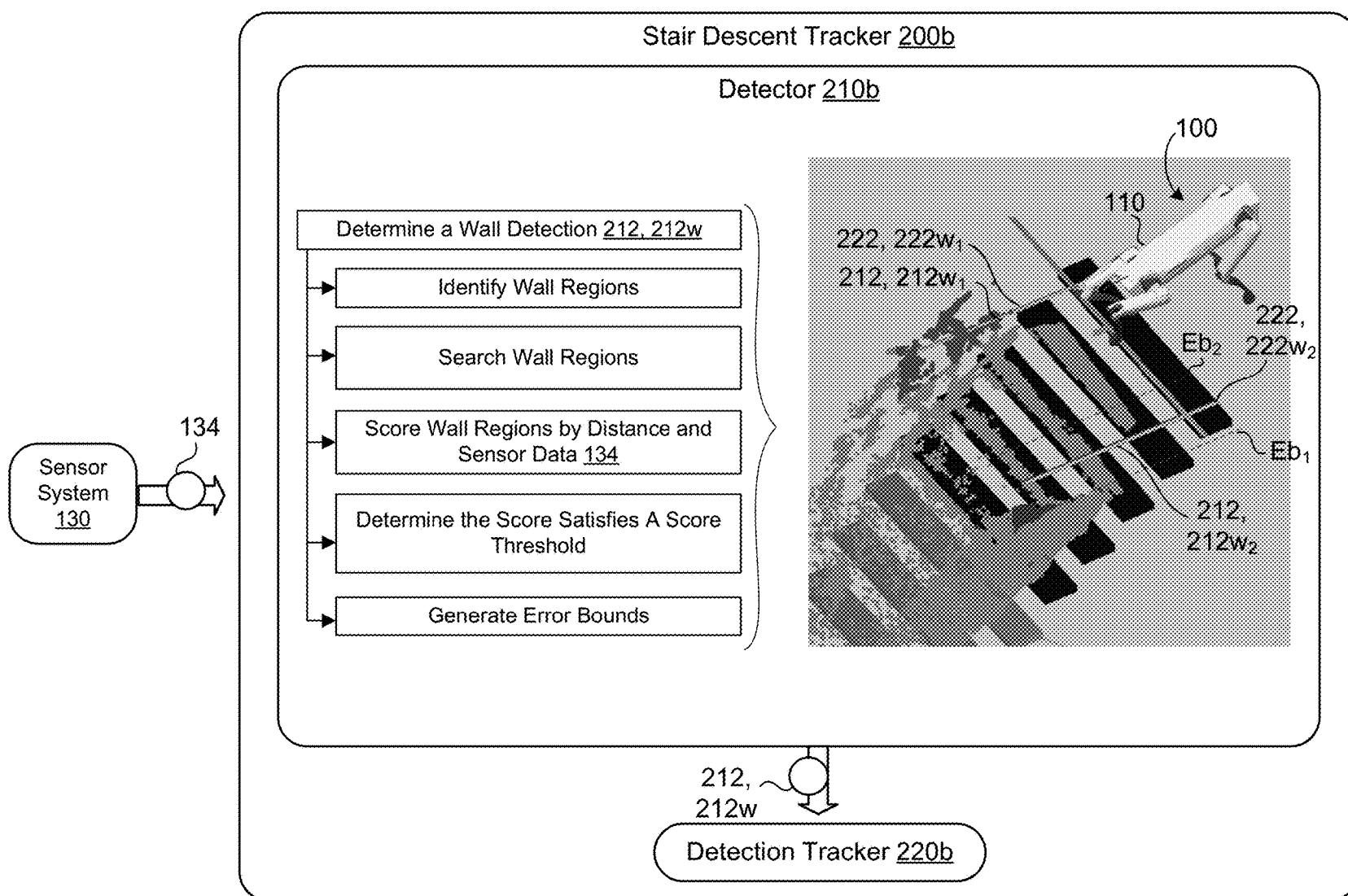


FIG. 2Q

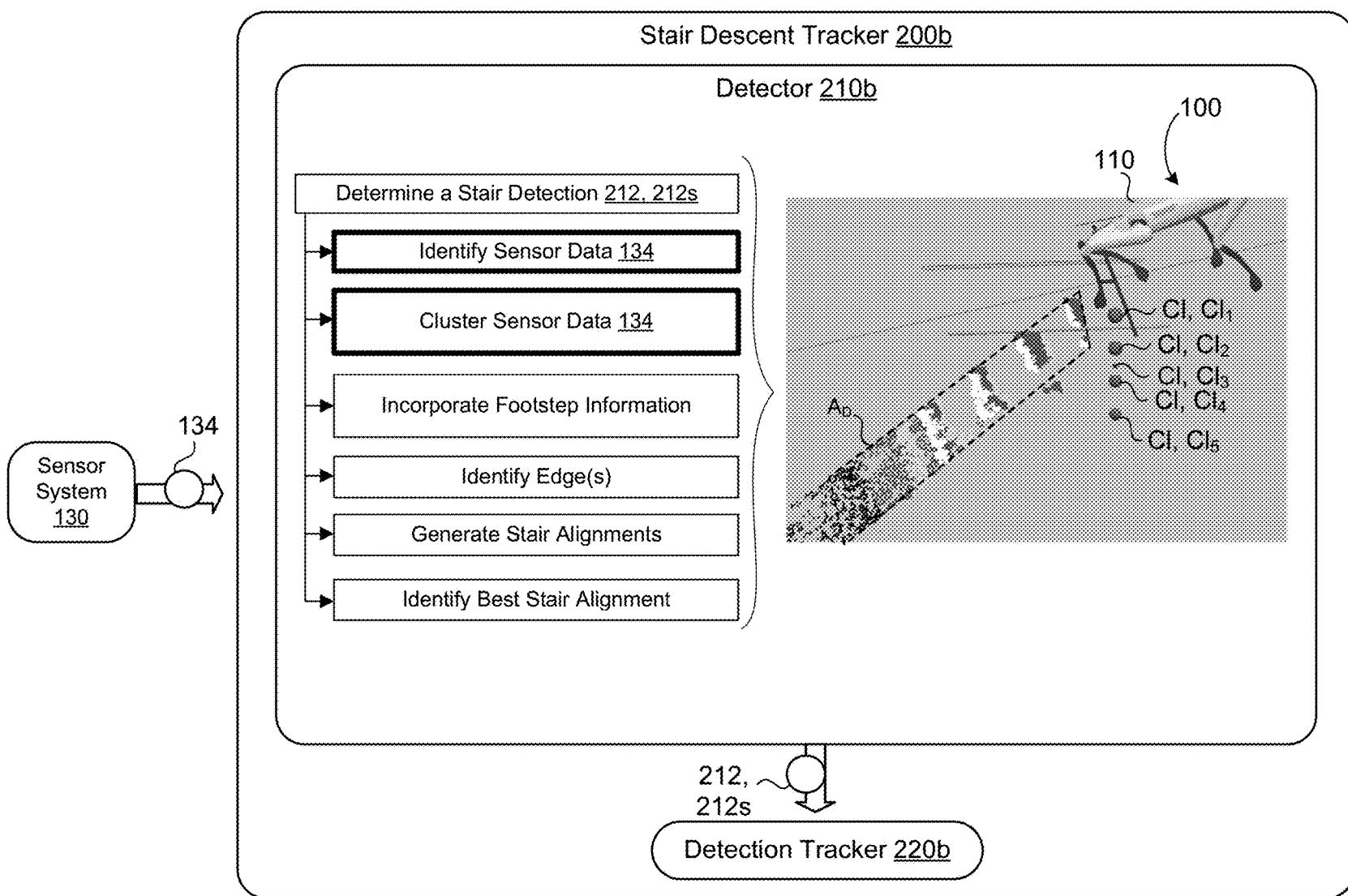


FIG. 2R

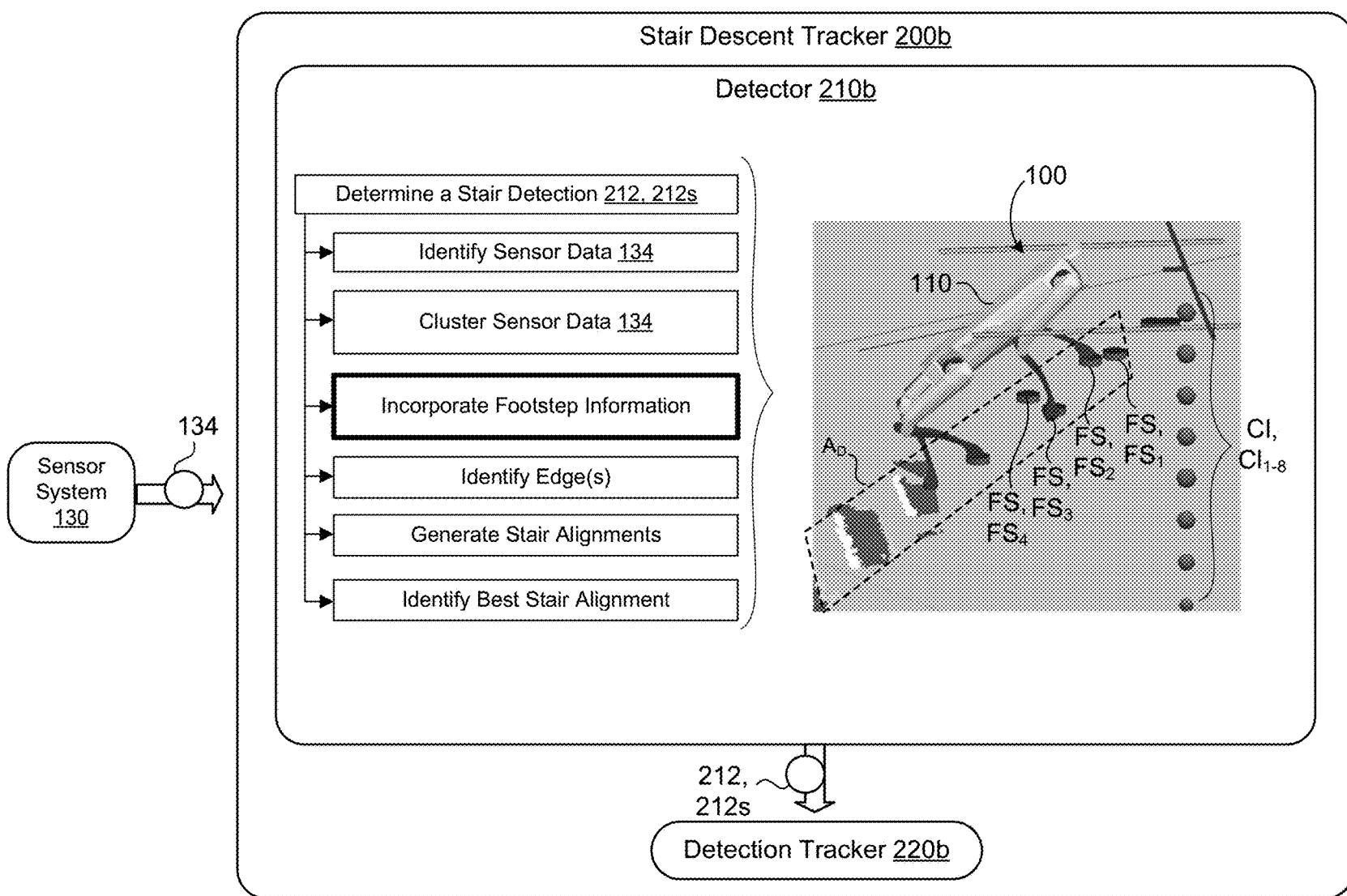


FIG. 2S

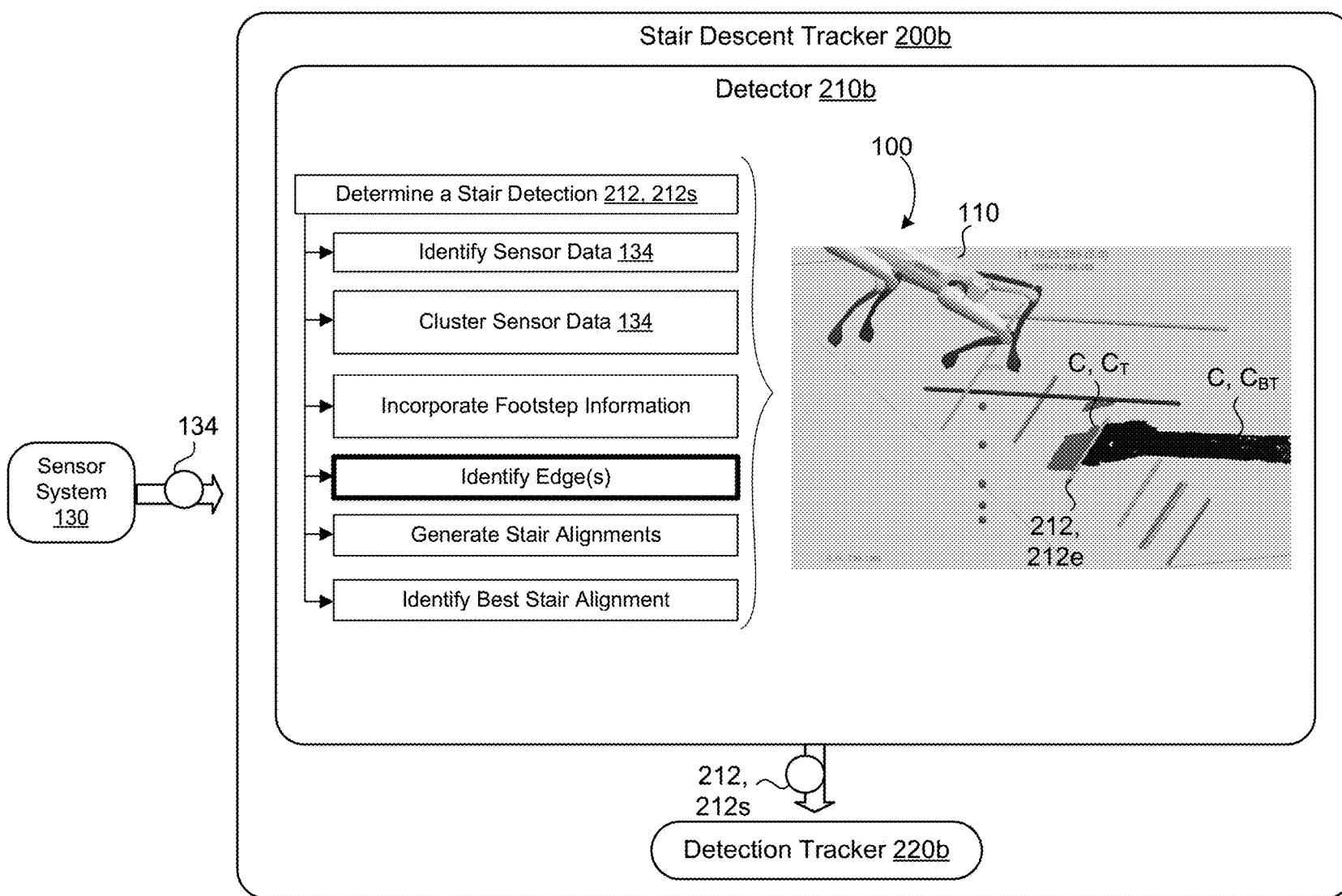


FIG. 2T

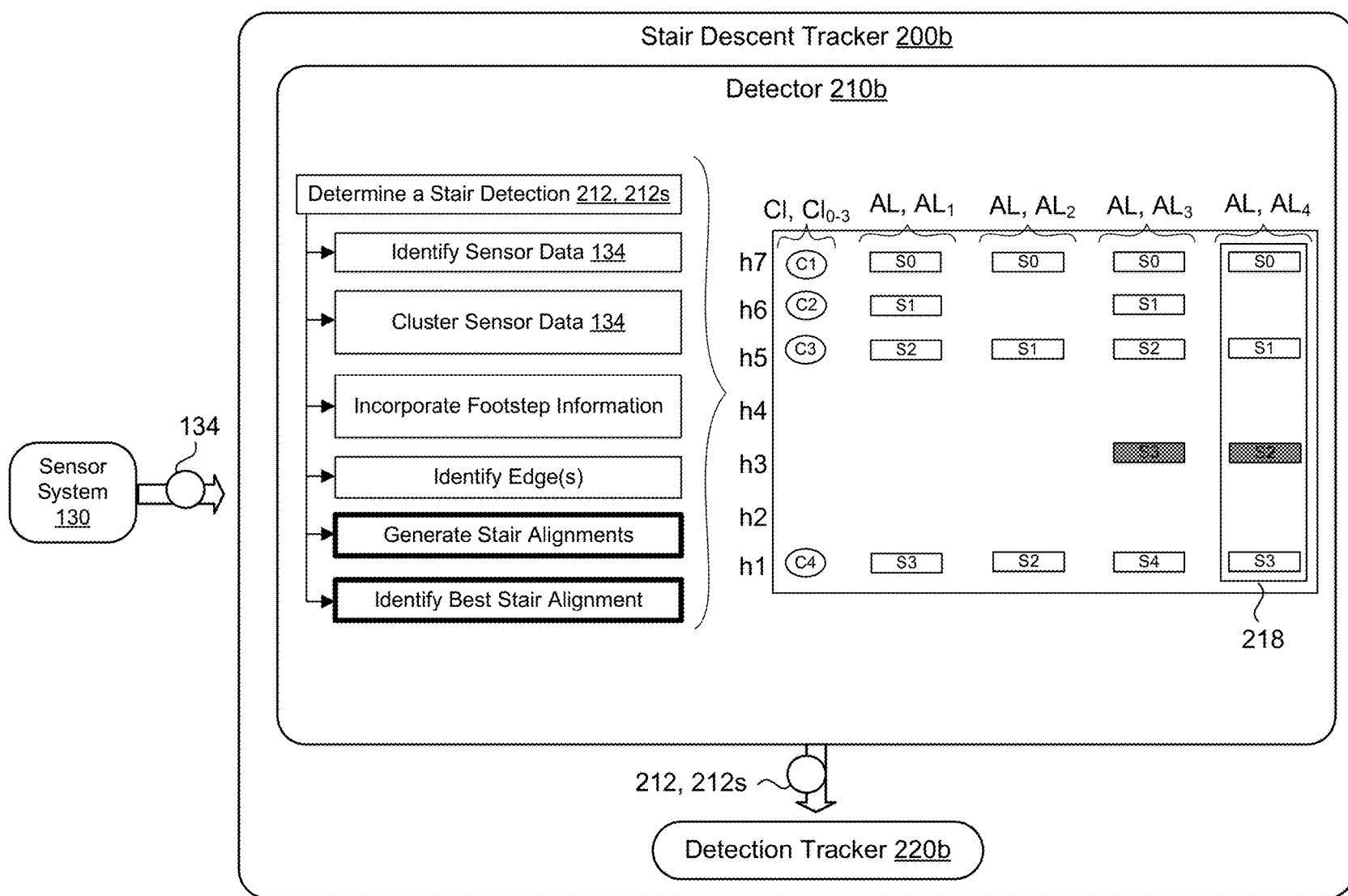


FIG. 2U

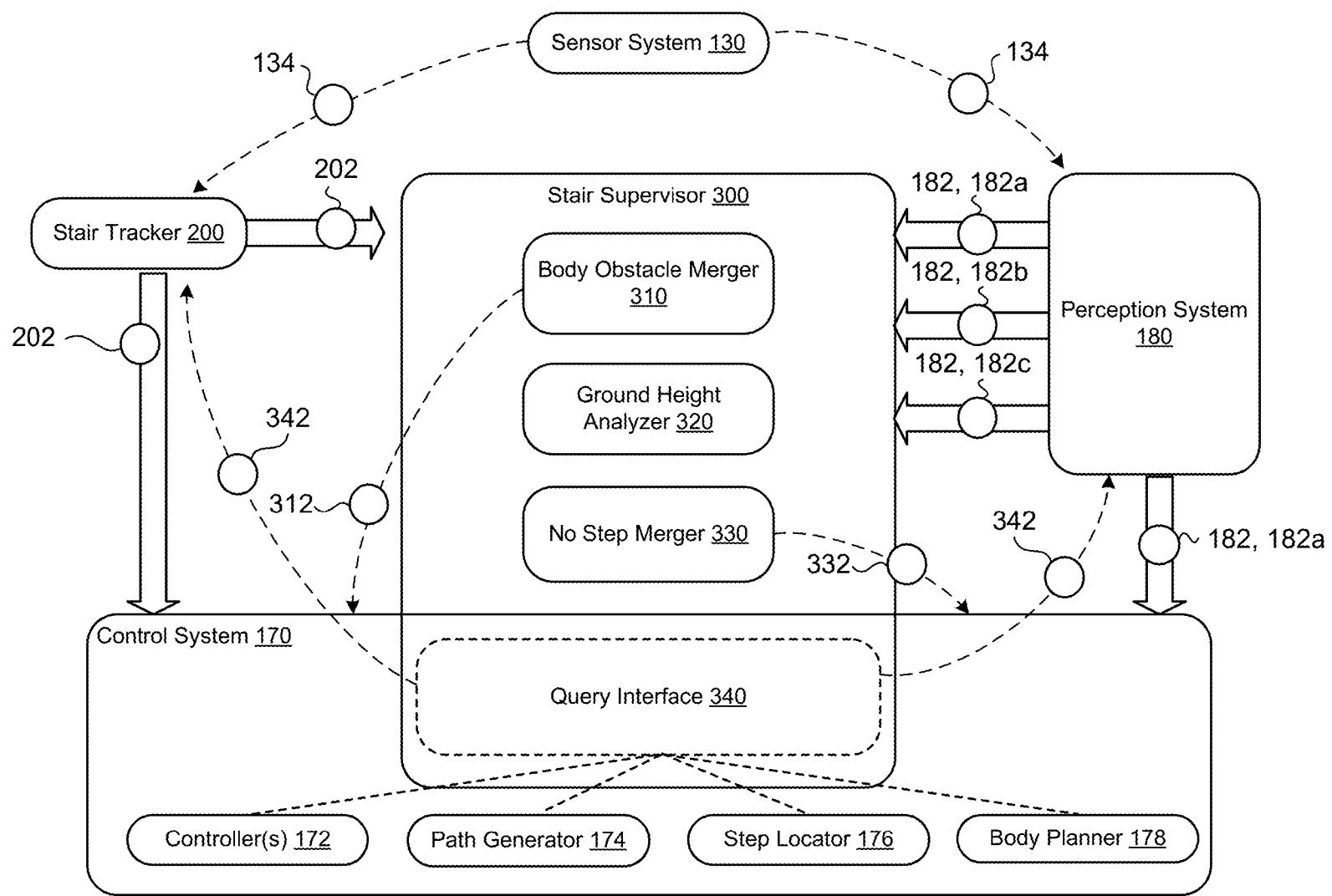


FIG. 3A

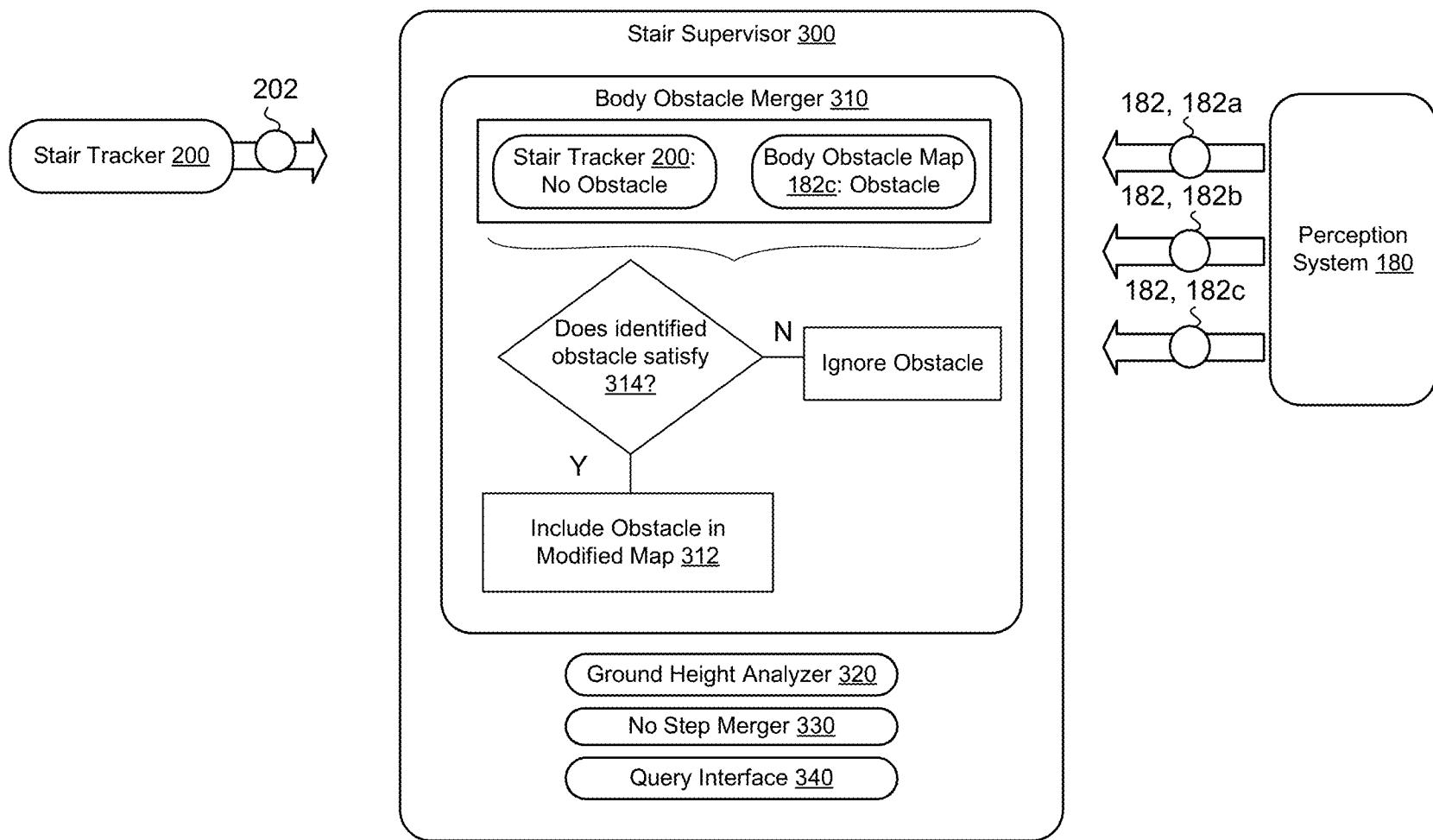


FIG. 3B

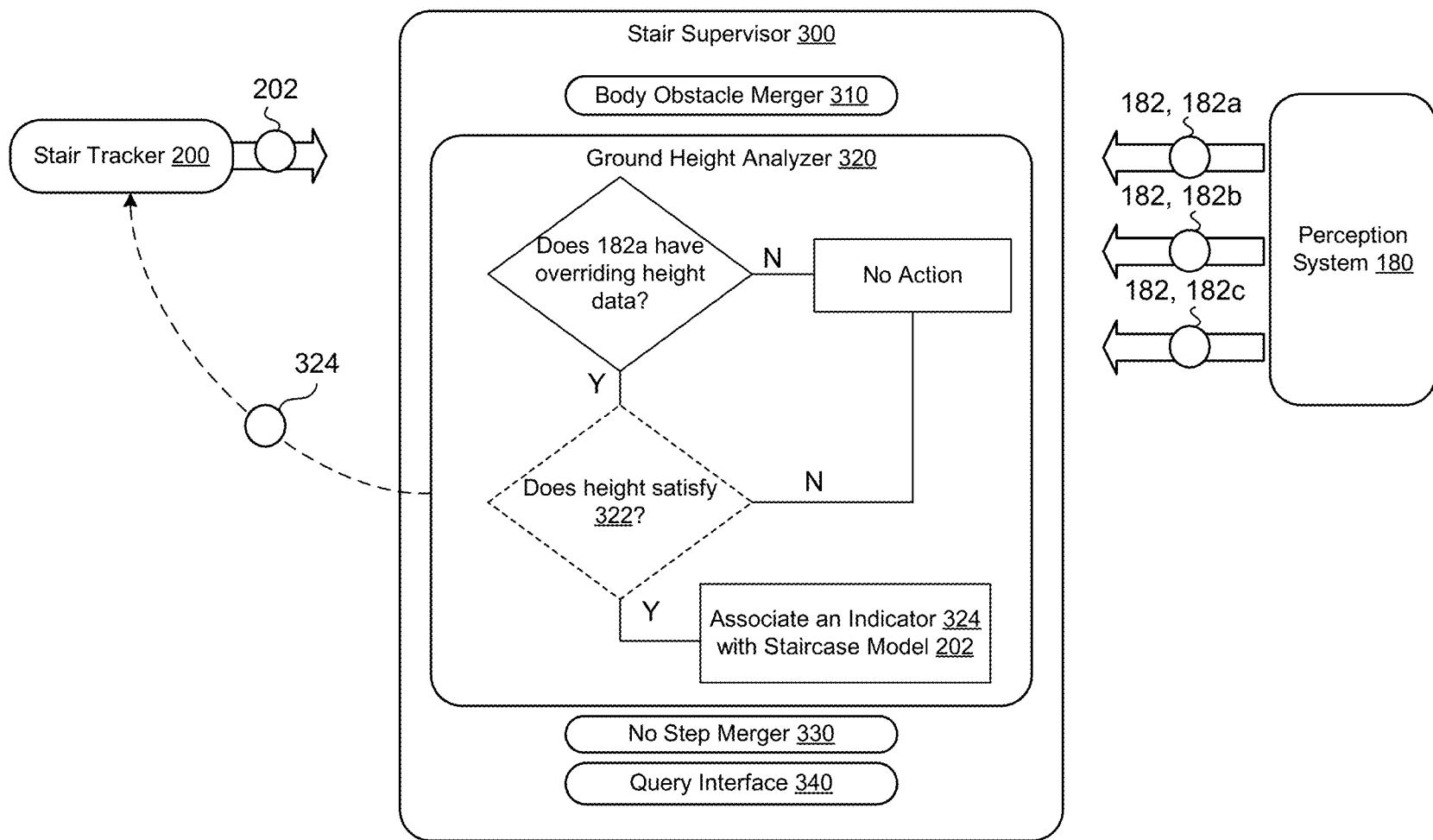


FIG. 3C

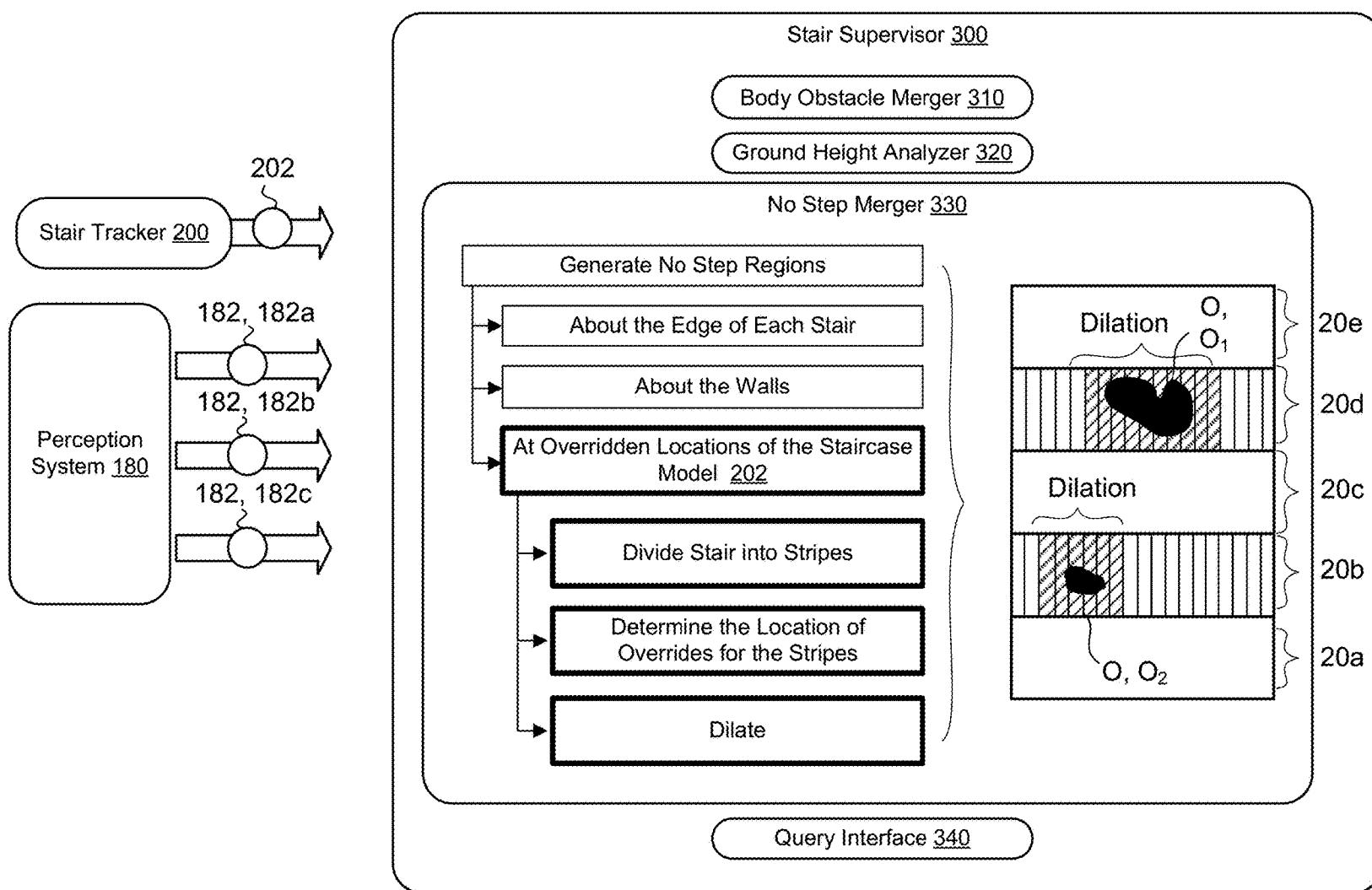


FIG. 3D

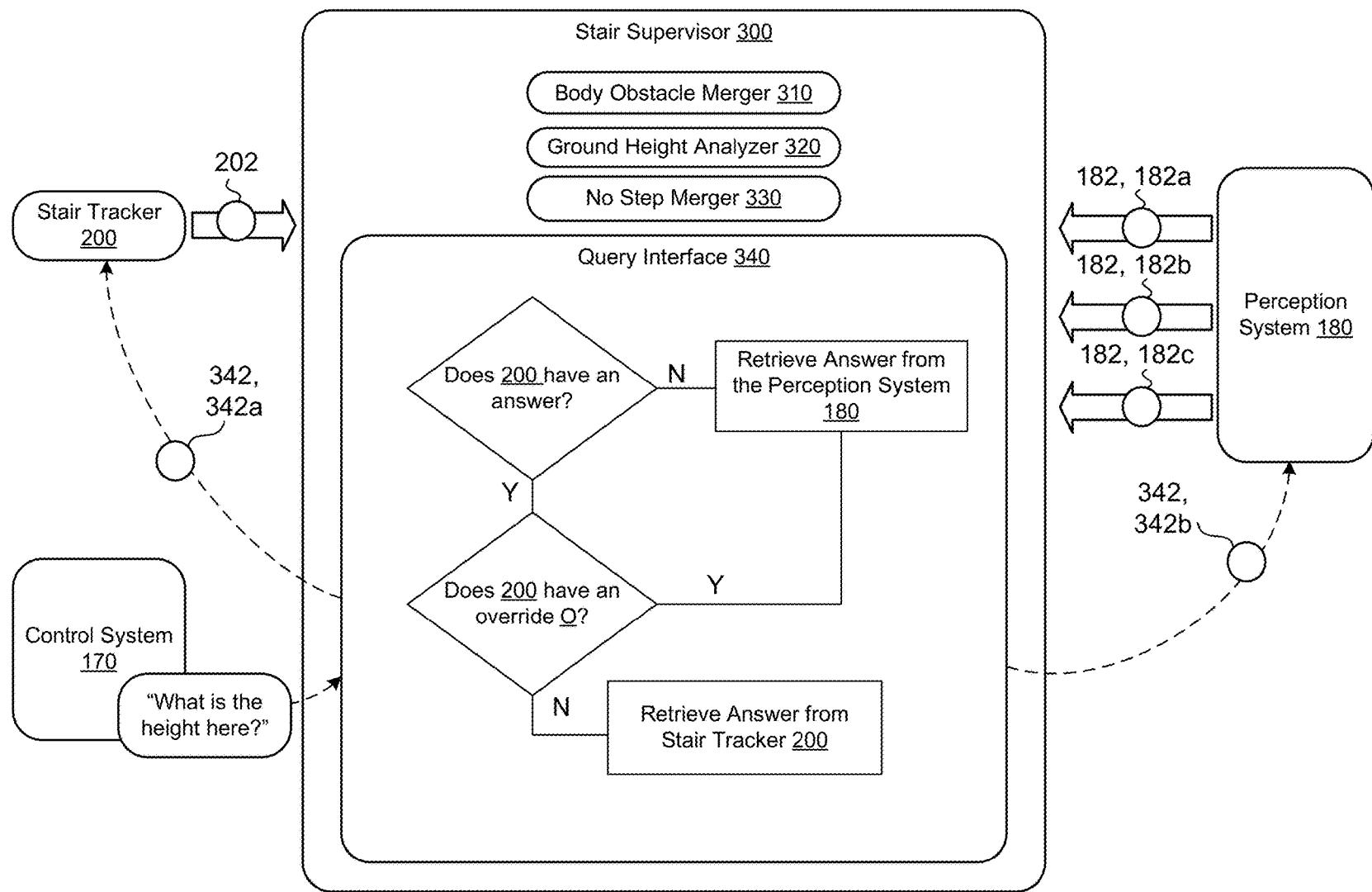


FIG. 3E

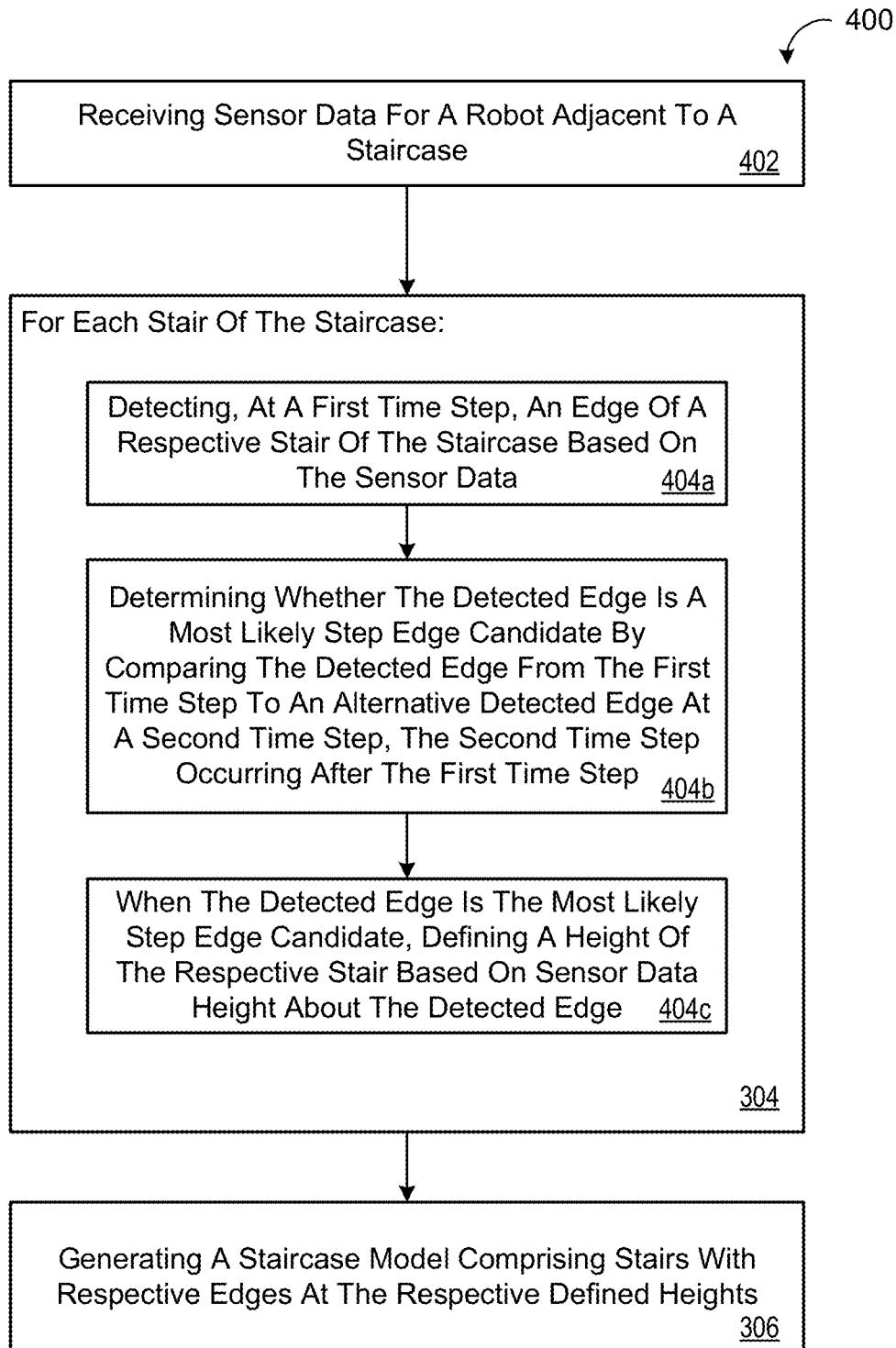


FIG. 4

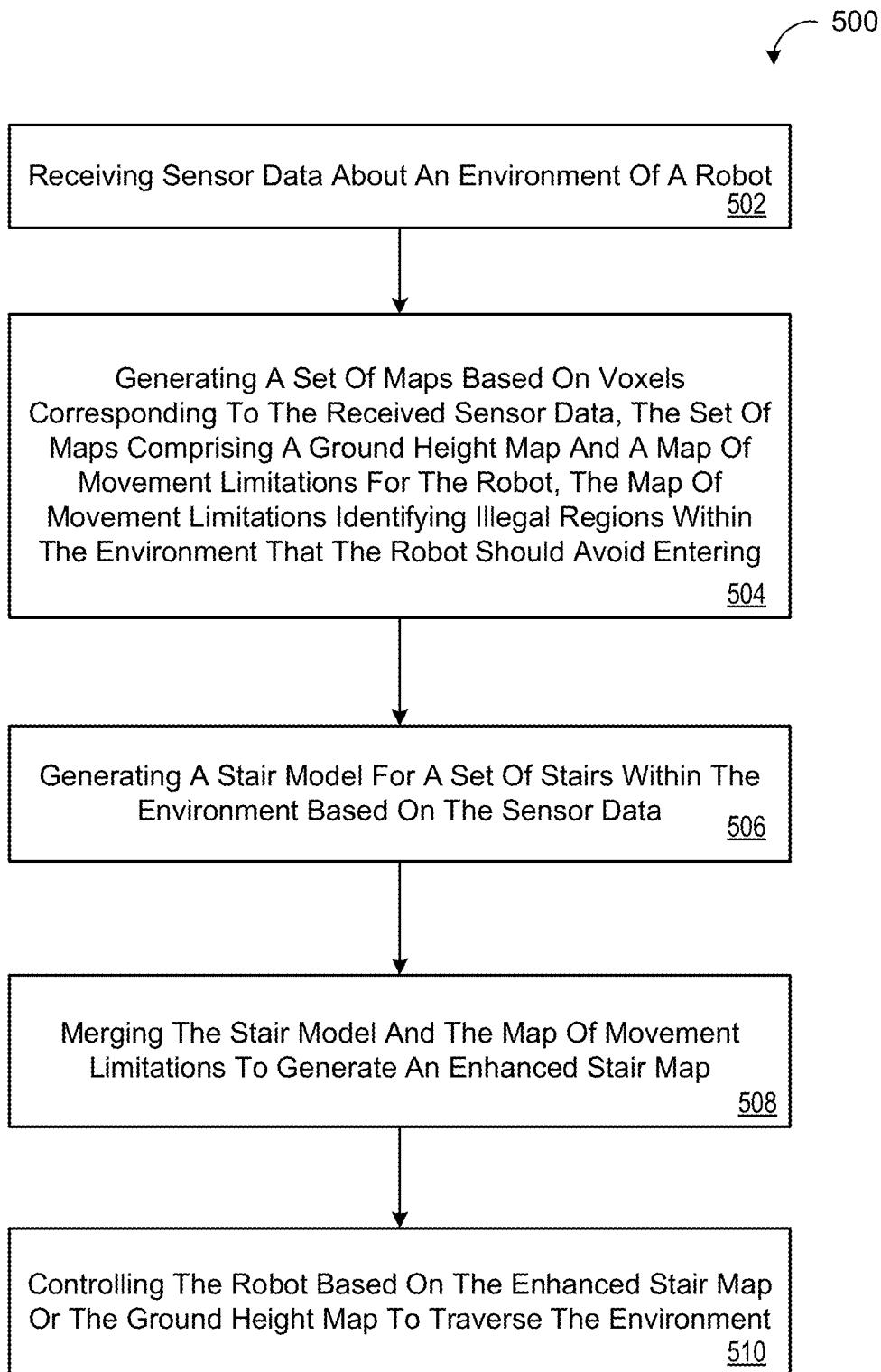


FIG. 5

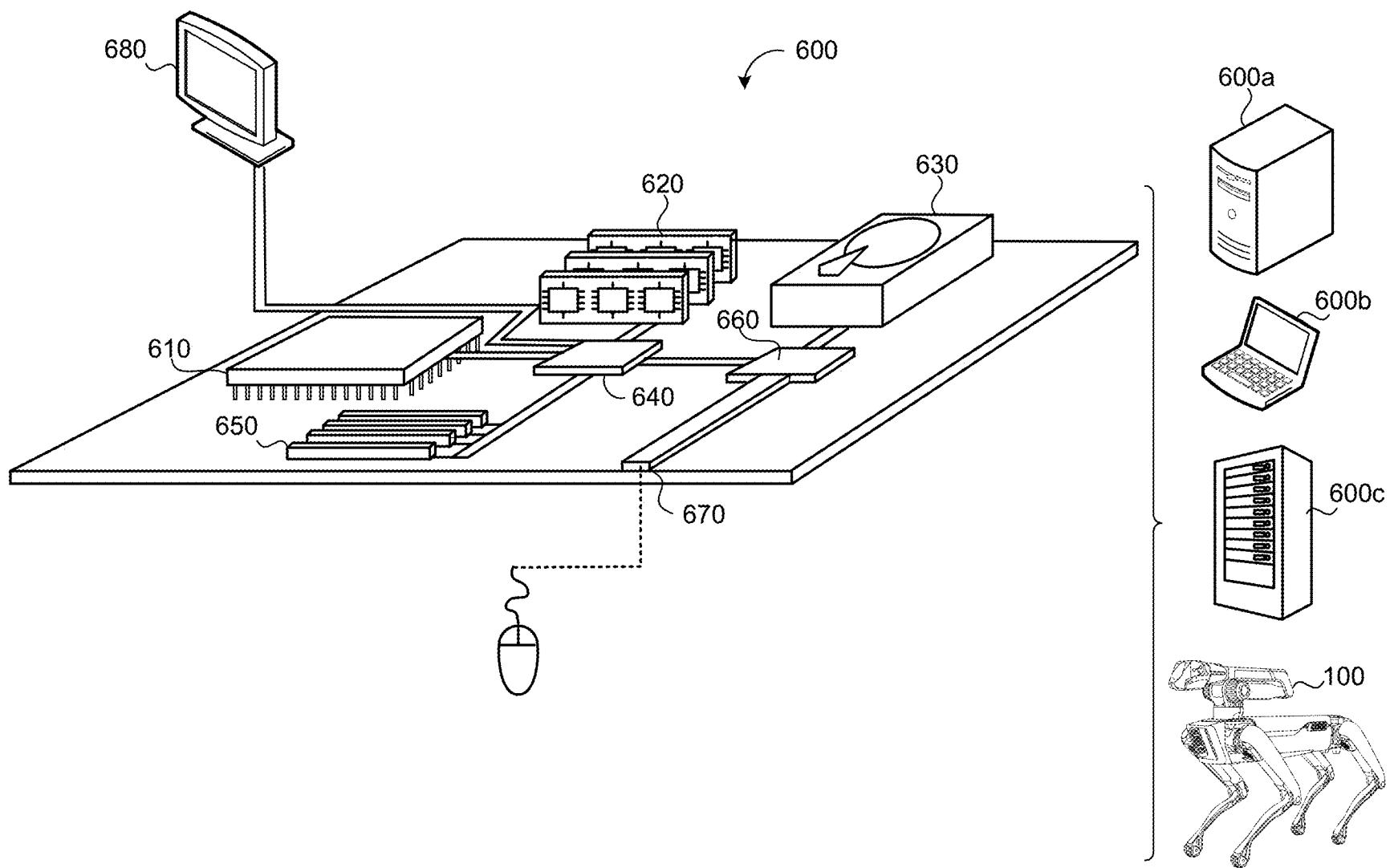


FIG. 6

PERCEPTION AND FITTING FOR A STAIR TRACKER

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This U.S. patent application claims priority under 35 U.S.C. § 120 to U.S. patent application Ser. No. 17/157,298, filed on Jan. 25, 2021 and to U.S. patent application Ser. No. 17/157,500, filed on Jan. 25, 2021. U.S. patent application Ser. No. 17/157,298 claims priority under 35 U.S.C. § 120 to U.S. patent application Ser. No. 16/382,390 filed on Apr. 12, 2019. U.S. patent application Ser. No. 17/157,500 claims priority under 35 U.S.C. § 120 to U.S. patent application Ser. No. 16/877,721, filed on May 19, 2020, which claims priority under 35 U.S.C. § 119(e) to U.S. Provisional Application 63/013,677, filed on Apr. 22, 2020. The disclosures of these prior applications are considered part of the disclosure of this application and are hereby incorporated by reference in their entireties.

TECHNICAL FIELD

[0002] This disclosure relates to perception and fitting for a stair mode.

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., using 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 or features requiring various means of coordinated leg movement provides additional benefits to such industries.

SUMMARY

[0004] One aspect of the disclosure provides method for perception and fitting for a stair tracker. The method includes receiving, at data processing hardware, sensor data for a robot adjacent to a staircase. For each stair of the staircase, the method includes detecting, by the data processing hardware at a first time step, an edge of a respective stair of the staircase based on the sensor data. For each stair of the staircase, the method also includes determining, by the data processing hardware, whether the detected edge is a most likely step edge candidate by comparing the detected edge from the first time step to an alternative detected edge at a second time step. The second time step occurs after the first time step. When the detected edge is the most likely step edge candidate, the method includes defining, by the data processing hardware, a height of the respective stair based on sensor data height about the detected edge. The method also includes generating, by the data processing hardware, a staircase model including stairs with respective edges at the respective defined heights.

[0005] Implementations of the disclosure may include one or more of the following optional features. In some implementations, for each stair of the staircase, the method

includes estimating, by the data processing hardware at a third time step, a wall location at an end of the detected edge of the respective stair of the staircase based on the sensor data. In this implementation, the method also includes determining, by the data processing hardware, whether the estimated wall location is a most likely wall location candidate by comparing the estimated wall location from the third time step to an alternative wall location at a fourth time step, the fourth time step occurring after the third time step. When the estimated wall location is the most likely wall location candidate, the method further includes defining, by the data processing hardware, the estimated wall location as a respective wall location at an end of the respective stair, the respective wall location designating a boundary for the robot while traversing the staircase. Also in this implementation, generating the staircase model includes generating one or more walls at the respective defined wall location for each stair of the staircase. Here, the third time step for estimating the wall location may coincide with the first time step for detecting the edge of the respective stair of the staircase. In some examples, defining the height of the respective stair includes identifying points from a point cloud of the sensor data that exist about the detected edge and defining the height of the respective stair based on an average of heights of the identified points from the point cloud that exist about the detected edge.

[0006] In some configurations, detecting the edge of the respective stair of the staircase at the first time step includes identifying points from a point cloud of sensor data that occur within a target detection box, the target detection box located at a position relative to a previously identified stair of the staircase. Here, detecting, at the first time step, the edge of the respective stair of the staircase may include traversing, using a detection column, the identified points from the point cloud of sensor data that occur within the target detection box in an upwards direction towards the robot and at an angle with respect to a gravitational axis of the robot, the detection column traversing the target detection box based on columnar increments of the target detection box. While traversing the identified points within the target detection box using the detection column, the method may include determining that the detection column is an empty set. Here, the method may also include identifying one or more respective points of a most recent non-empty set for the detection column as one or more points along the edge of the respective stair of the staircase, the one or more respective points within a cell of the detection column, the cell having the greatest height within the detection column and most towards the robot. The method may further include generating an initial edge line from the one or more respective points identified using the detection column, removing outlier sensor data associated with the initial edge line, and generating a refined edge line from the one or more respective points of the initial edge line once the outlier sensor data is removed using the least squares fit. The initial edge line may be generated using a least squares fit.

[0007] In some implementations, when the respective step is a first step of the staircase closest to a support surface of the staircase, detecting the edge of the respective stair of the staircase at the first time step includes classifying points in a point cloud of the sensor data based on a height of a foot of the robot in contact with the support surface. In this implementation, the points classified are as ground points at a first height range with respect to the height of the foot of

the robot and first step points at a second height range with respect to the height of the foot of the robot, the second height range greater than the first height range.

[0008] In some examples, the robot is initially located atop the staircase. Here, for a floor edge corresponding to a respective edge of a top stair of the staircase, the method may include classifying, by the data processing hardware, the sensor data into height classifications, each height classification corresponding to a height along an axis parallel to a gravitational axis of the robot and classifying the height of the sensor data relative to a floor beneath the robot, the floor including the floor edge. Further, for a floor edge corresponding to a respective edge of a top stair of the staircase, the method may include identifying, by the data processing hardware, a plurality of points along the floor edge based on a change in height classifications between portions of the sensor data, the change defined as either (i) a first transition from sensor data classified as a floor height to a portion of missing sensor data or (ii) a second transition from sensor data classified as a floor height to sensor data classified as below the floor height. For a floor edge corresponding to a respective edge of a top stair of the staircase, the method may also include generating, by the data processing hardware, a line fit to the plurality of points along the floor edge. Here, detecting the floor edge of the top stair of the staircase may detect the line fit to the plurality of points along the floor edge as the detected edge. The method may include associating, by the data processing hardware, a respective height classification with each pixel within a two-dimensional (2D) image space representing the classified sensor data. Here, identifying the plurality of points along the floor edge includes searching each pixel of the 2D image space for the change in height classifications. The method may include refining the line fit to the plurality of points along the floor edge by removing outlier points from the plurality of points.

[0009] Another aspect of the disclosure provides a robot. The robot includes a body and two or more legs coupled to the body and configured to traverse an environment. The robot also includes a stair modeling system in communication with the robot. The modeling system includes data processing hardware and 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. The operations include receiving sensor data for the robot adjacent to a staircase. For each stair of the staircase, the operations include detecting, at a first time step, an edge of a respective stair of the staircase based on the sensor data. For each stair of the staircase, the operations also include determining whether the detected edge is a most likely step edge candidate by comparing the detected edge from the first time step to an alternative detected edge at a second time step, the second time step occurring after the first time step. For each stair of the staircase, when the detected edge is the most likely step edge candidate, the operations include defining a height of the respective stair based on sensor data height about the detected edge. For each stair of the staircase, the operations further include generating a staircase model including stairs with respective edges at the respective defined heights.

[0010] This aspect may include one or more of the following optional features. In some configurations, for each stair of the staircase the operations include estimating, at a third time step, a wall location at an end of the detected edge

of the respective stair of the staircase based on the sensor data and determining whether the estimated wall location is a most likely wall location candidate by comparing the estimated wall location from the third time step to an alternative wall location at a fourth time step, the fourth time step occurring after the third time step. In this configuration, when the estimated wall location is the most likely wall location candidate, the operations include defining the estimated wall location as a respective wall location at an end of the respective stair, the respective wall location designating a boundary for the robot while traversing the staircase. Further, in this configuration, generating the staircase model includes generating one or more walls at the respective defined wall location for each stair of the staircase. Here, the third time step for estimating the wall location may coincide with the first time step for detecting the edge of the respective stair of the staircase. In some examples, defining the height of the respective stair includes identifying points from a point cloud of the sensor data that exist about the detected edge and defining the height of the respective stair based on an average of heights of the identified points from the point cloud that exist about the detected edge.

[0011] In some implementations, detecting the edge of the respective stair of the staircase at the first time step includes identifying points from a point cloud of sensor data that occur within a target detection box, the target detection box located at a position relative to a previously identified stair of the staircase. Here, detecting, at the first time step, the edge of the respective stair of the staircase may include traversing, using a detection column, the identified points from the point cloud of sensor data that occur within the target detection box in an upwards direction towards the robot and at an angle with respect to a gravitational axis of the robot, the detection column traversing the target detection box based on columnar increments of the target detection box. While traversing the identified points within the target detection box using the detection column, the operations may include determining that the detection column is an empty set. Further, detecting, at the first time step, the edge of the respective stair of the staircase may include identifying one or more respective points of a most recent non-empty set for the detection column as one or more points along the edge of the respective stair of the staircase, the one or more respective points within a cell of the detection column, the cell having the greatest height within the detection column and most towards the robot. The operations may also include generating an initial edge line from the one or more respective points identified using the detection column, removing outlier sensor data associated with the initial edge line, and generating a refined edge line from the one or more respective points of the initial edge line once the outlier sensor data is removed using the least squares fit. The initial edge line may be generated using a least squares fit.

[0012] In some examples, when the respective step is a first step of the staircase closest to a support surface of the staircase, detecting the edge of the respective stair of the staircase at the first time step includes classifying points in a point cloud of the sensor data based on a height of a foot of the robot in contact with the support surface. In this example, the points are classified as ground points at a first height range with respect to the height of the foot of the robot and first step points at a second height range with

respect to the height of the foot of the robot, the second height range greater than the first height range.

[0013] In some configurations, the robot is initially located atop the staircase. Here, the operations may include, for a floor edge corresponding to a respective edge of a top stair of the staircase, classifying the sensor data into height classifications, each height classification corresponding to a height along an axis parallel to a gravitational axis of the robot and classifying the height of the sensor data relative to a floor beneath the robot, the floor including the floor edge. Here, the operations may also include identifying a plurality of points along the floor edge based on a change in height classifications between portions of the sensor data, the change defined as either (i) a first transition from sensor data classified as a floor height to a portion of missing sensor data or (ii) a second transition from sensor data classified as a floor height to sensor data classified as below the floor height, and generating a line fit to the plurality of points along the floor edge. Detecting the floor edge of the top stair of the staircase may detect the line fit to the plurality of points along the floor edge as the detected edge. Optionally, the operations may include associating a respective height classification with each pixel within a two-dimensional (2D) image space representing the classified sensor data and identifying the plurality of points along the floor edge may include searching each pixel of the 2D image space for the change in height classifications. The operations may include refining the line fit to the plurality of points along the floor edge by removing outlier points from the plurality of points.

[0014] 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

[0015] FIG. 1A is a perspective view of an example robot standing atop a landing of a staircase.

[0016] FIG. 1B is a schematic view of example systems of the robot of FIG. 1A.

[0017] FIGS. 2A and 2B are schematic views of example stair trackers for the robot of FIG. 1A.

[0018] FIGS. 2C-2I are schematic views of example stair ascent trackers for the robot of FIG. 1A.

[0019] FIGS. 2J-2U are schematic views of example stair descent trackers for the robot of FIG. 1A.

[0020] FIGS. 3A-3E are schematic views of example stair supervisors for the robot of FIG. 1A.

[0021] FIG. 4 is a flow chart of an example arrangement of operations for a method of generating a staircase model.

[0022] FIG. 5 is a flow chart of an example arrangement of operations for a method of controlling a robot based on fused modeled and perceived terrain.

[0023] FIG. 6 is a schematic view of an example computing device that may be used to implement the systems and methods described herein.

[0024] Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0025] As legged-robots maneuver about environments, the robots may encounter terrain (e.g., human-made structures) that requires precise leg movement and foot place-

ment (i.e., distal end placement). To provide precise leg movement and foot placement, when systems of the robot recognize different types of terrain, the movement control systems of the robot may constrain the robot's movement to traverse the terrain in order to prevent mistakes, even small mistakes, which may lead to catastrophic issues for the robot. For example, when humans traverse stairs, this task requires a degree of coordination (e.g., eye-to-foot coordination). Without the coordination, a human may misstep, slip, trip, or fall on the stairs. Robots may encounter the same misfortunes, but lack natural coordination. Therefore, robots need systems and methods to coordinate precise leg movements.

[0026] FIG. 1A is an example of an environment **10** for a robot **100**. The environment **10** generally refers to a spatial area associated with some type of terrain including stairs **20**, **20a-n** or stair-like terrain that may be traversed by the robot **100** (e.g., using a control system **170** as shown in FIG. 1B). Systems of the robot **100** are responsible for coordinating and/or moving the robot **100** about the environment **10**. As the robot **100** traverses stairs **20** or stair-like terrain and moves about the environment **10**, systems of the robot **100** may analyze the terrain, plan motion trajectories for the robot **100** (e.g., with a path generator **174**, a step planner **176**, a body planner **178**), and/or instruct the robot **100** to perform various movements (e.g., with a controller **172**). The robot **100** may use various systems of the robot **100** together to attempt to successfully traverse the environment **10** while avoiding collisions C and/or damage to the robot **100** or the robot's environment **10**.

[0027] Stairs **20**, **20a-n** generally refer to a group of more than one stair **20** (i.e., a group of n stairs **20**) designed to bridge a vertical distance. To bridge the vertical distance, stairs **20a-n** typically run a horizontal distance with a given rise in vertical height over a pitch (or pitch line). Each stair **20** traditionally includes a tread **22** and a riser **24**. The tread **22** of a stair **20** refers to a horizontal part of the stair **20** that is stepped on while a riser **24** refers to a vertical portion of the stair **20** between each tread **22**. The tread **22** of each stair **20** spans a tread depth "d" measuring from an outer edge **26** of a stair **20** to the riser **24** between stairs **20**. For a residential, a commercial, or an industrial structure, some stairs **20** also include nosing as part of the edge **26** for safety purposes. Nosing, as shown in FIG. 1A, is a part of the tread **22** that protrudes over a riser **24** beneath the tread **22**. For example, the nosing (shown as edge **26a**) is part of the tread **22a** and protrudes over the riser **24a**.

[0028] A set of stairs **20** may be preceded by or include a platform or support surface **12** (e.g., a level support surface). For example, a landing refers to a level platform or support surface **12** at a top of a set of stairs **20** or at a location between stairs **20**. For instance, a landing occurs where a direction of the stairs **20** changes or between a particular number of stairs **20** (i.e., a flight of stairs **20** that connects two floors). FIG. 1A illustrates the robot **100** standing on a landing at the top of a set of stairs **20**. Furthermore, a set of stairs **20** may be constrained between one or more walls **28** and/or railings. In some examples, a wall **28** includes a toe board (e.g., baseboard-like structure or runner at ends of the treads **22**) or a stringer. In the case of industrial stairs **20** that are not completely enclosed, industrial stairs **20** include a stringer that functions as a toe board (e.g., a metal stringer). [0029] Stair-like terrain more generally refers to terrain that varies in height over some distance. Stair-like terrain

may resemble stairs in terms of a change in elevation (e.g., an inclined pitch with a gain in elevation or a declined pitch with a loss in elevation). However, with stair-like terrain the delineation of treads 22 and risers 24 is not as obvious. Rather, stair-like terrain may refer to terrain with tread-like portions that allow a robot to have enough traction to plant a stance limb and sequentially or simultaneously use a leading limb to ascend or to descend over an adjacent vertical obstruction (resembling a riser) within the terrain. For example, stair-like terrain may include rubble, an inclined rock scramble, damaged or deteriorating traditional stairs, etc.

[0030] Referring to FIG. 1A, 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 J_H coupling an upper member 122, 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. For impact detection, the hip joint J_H may be further broken down into abduction-adduction rotation of the hip joint J_H designated as " J_{Hx} " for occurring in a frontal plane of the robot 100 (i.e., a X-Z plane extending in directions of a x-direction axis A_x and the z-direction axis A_z) and a flexion-extension rotation of the hip joint J_H designated as " J_{Hy} " for occurring in a sagittal plane of the robot 100 (i.e., a Y-Z plane extending in directions of a y-direction axis A_y and the z-direction axis A_z). Although FIG. 1A 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) that provide a means to traverse the terrain within the environment 10.

[0031] In order to traverse the terrain, each leg 120 has a distal end 124 that contacts a surface 12 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.

[0032] 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 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 (i.e., vertical distance) generally refers to a distance along (e.g., parallel to) the z-direction (i.e., z-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 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 support surface 12 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 .

[0033] When a legged-robot moves about the environment 10, the legs 120 of the robot undergo a gait cycle. Generally, a gait cycle begins when a leg 120 touches down or contacts a support surface 12 and ends when that same leg 120 once again contacts the ground surface 12. Here, touchdown is also referred to as a footfall defining a point or position where the distal end 124 of a locomotion-based structure 120 falls into contact with the support surface 12. The gait cycle may predominantly be divided into two phases, a swing phase and a stance phase. During the swing phase, a leg 120 performs (i) lift-off from the support surface 12 (also sometimes referred to as toe-off and the transition between the stance phase and swing phase), (ii) flexion at a knee joint J_K of the leg 120, (iii) extension of the knee joint J_K of the leg 120, and (iv) touchdown (or footfall) back to the support surface 12. Here, a leg 120 in the swing phase is referred to as a swing leg 120_{sw}. As the swing leg 120_{sw} proceeds through the movement of the swing phase 120_{sw}, another leg 120 performs the stance phase. The stance phase refers to a period of time where a distal end 124 (e.g., a foot) of the leg 120 is on the support surface 12. During the stance phase a leg 120 performs (i) initial support surface contact which triggers a transition from the swing phase to the stance phase, (ii) loading response where the leg 120 dampens support surface contact, (iii) mid-stance support for when the contralateral leg (i.e., the swing leg 120_{sw}) lifts-off and swings to a balanced position (about halfway through the swing phase), and (iv) terminal-stance support from when the robot's COM is over the leg 120 until the contralateral leg 120 touches down to the support surface 12. Here, a leg 120 in the stance phase is referred to as a stance leg 120_{st}.

[0034] In order to maneuver about the environment 10, the robot 100 includes a sensor system 130 with one or more sensors 132, 132_{a-n} (e.g., shown as a first sensor 132, 132_a and a second sensor 132, 132_b). 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 scanning light-detection and ranging (LIDAR) sensor, or a scanning laser-detection and ranging (LADAR) sensor. In some configurations, the robot 100 includes two stereo cameras as sensors 132 at a front end of the body 110 of the robot 100 (i.e., a head of the robot 100 adjacent the front legs 120_{a-b} of the robot 100) and one stereo camera as a sensor 132 at a back end of the body 110 of the robot 100 adjacent rear legs 120_{c-d} of the robot 100. 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. 1A 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).

[0035] Referring to FIGS. 1A and 1B, in some implementations, the sensor system **130** includes sensor(s) **132** coupled to a joint J. In some examples, these sensors **132** couple to a motor that operates a joint J of the robot **100** (e.g., sensors **132**, **132a-b**). Here, these sensors **132** generate joint dynamics **134**, **134_{JD}** in the form of joint-based sensor data **134**. Joint dynamics **134_{JD}** collected as joint-based sensor data **134** may include joint angles (e.g., an upper member **122_U** relative to a lower member **122_L**), joint speed (e.g., joint angular velocity or joint angular acceleration), and/or joint torques experienced at a joint J (also referred to as joint forces). Here, joint-based sensor data **134** generated by one or more sensors **132** may be raw sensor data, data that is further processed to form different types of joint dynamics **134_{JD}**, 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.

[0036] 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 . 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** of the robot **100**. With the sensor data **134**, a perception system **180** of the robot **100** may generate maps **182** for the terrain about the environment **10**.

[0037] While the robot **100** maneuvers about the environment **10**, the sensor system **130** gathers sensor data **134** relating to the terrain of the environment **10** and/or structure of the robot **100** (e.g., joint dynamics and/or odometry of the robot **100**). For instance, FIG. 1A depicts the robot **100** standing on a landing (i.e., level support surface) of a set of stairs **20** as the environment **10** of the robot **100**. Here, the sensor system **130** gathering sensor data **134** about the set of stairs **20**. As the sensor system **130** gathers sensor data **134**, a computing system **140** is configured to store, to process, and/or to communicate the sensor data **134** to various systems of the robot **100** (e.g., the control system **170**, the perception system **180**, a stair tracker **200**, and/or a stair supervisor **300**). 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**.

[0038] With continued reference to FIGS. 1A and 1B, 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**).

[0039] Additionally or alternatively, the computing system **140** includes computing resources that are located remotely from the robot **100**. For instance, the computing system **140** may communicate via a network **150** with a remote system **160** (e.g., a remote computer/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 some 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**.

[0040] 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**.

[0041] 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**, a stair tracker **200**, and/or a stair supervisor **300**). The control system **170** performs operations and other functions using hardware **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 control system **170**, the perception system **180**, a stair tracker **200**, and/or a stair supervisor **300**). 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.

[0042] In some examples, the controller 172 includes a plurality of controllers 172 where each of the controllers 172 has a fixed cadence. A fixed cadence refers to a fixed timing for a step or swing phase of a leg 120. For example, the controller 172 instructs the robot 100 to move the legs 120 (e.g., take a step) at a particular frequency (e.g., step every 250 milliseconds, 350 milliseconds, etc.). With a plurality of controllers 172 where each controller 172 has a fixed cadence, the robot 100 can experience variable timing by switching between controllers 172. In some implementations, the robot 100 continuously switches/selects fixed cadence controllers 172 (e.g., re-selects a controller 170 every three milliseconds) as the robot 100 traverses the environment 10.

[0043] In some implementations, the control system 170 includes specialty controllers 172 that are dedicated to a particular control purpose. For example, the control system 170 may include one or more stair controllers 172 dedicated to planning and coordinating the robot's movement to traverse a set of stairs 20. For instance, a stair controller 172 may ensure the footpath for a swing leg 120_{sw} maintains a swing height to clear a riser 24 and/or edge 26 of a stair 20. Other 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 perceptions system 180 (e.g., map(s) 182). The body planner 178, much like the step locator 176, receives inputs from the perceptions 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.

[0044] 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.

[0045] In some examples, the one or more maps 182 generated by the perception system 180 are a ground height map 182, 182a, a no step map 182, 182b, and a body obstacle map 182, 182c. The ground height map 182a refers to a map 182 generated by the perception system 180 based on voxels from a voxel map. In some implementations, the

ground height map 182a 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 182a), the ground height map 182a specifies a height. In other words, the ground height map 182a conveys that, at a particular X-Y location in a horizontal plane, the robot 100 should step at a certain height.

[0046] The no step map 182b 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 182c and the ground height map 182a, the no step map 182b 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 182b, 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 182b includes a signed-distance field. Here, the signed-distance field for the no step map 182b includes a distance to a boundary of an obstacle (e.g., a distance to a boundary of the no step region 244) and a vector v (e.g., defining nearest direction to the boundary of the no step region 244) to the boundary of an obstacle.

[0047] The body obstacle map 182c 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 182c 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 182c 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 182 generates the body obstacle map 182c according to a grid of cells (e.g., a grid of the X-Y plane). Here, each cell within the body obstacle map 182c 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).

[0048] Since the robot 100 navigates about an environment 10 based on some interpretation of sensor data 134 captured by one or more sensors 132 about the robot 100, situations arise where certain types of structures within the environment 10 may routinely result in poor sensor data 134. Unfortunately, even when poor sensor data 134 exists, the robot 100 may still attempt to navigate and/or to perform tasks within the environment 10. One type of structure that often leads to poor sensor data 134 is stairs 20. This is particularly problematic because stairs 20 are a fairly common structural feature both commercially and residentially. Furthermore, poor sensor data 134 for stair navigation may be catastrophic because stairs also generally demand precise

leg movement and foot placement. Since stairs may be a difficult feature to navigate from a coordination perspective, poor sensor data 134 may significantly compound the navigational challenges.

[0049] A sensor 132 may produce poor sensor data 134 for a variety of reasons, but stairs 20 are actually a structure that is more susceptible to sensor data issues. With regard to stairs 20, two separate problems may commonly occur. One problem generally pertains to stair ascent while the other problem pertains to stair descent. For stair ascent, open riser stairs 20 pose issues for the robot 100. With open riser stairs 20, the sensor(s) 132 of the robot 100 may be at a sensing height equal to a height of one or more stairs 20. At this height, the sensor 132 generates far sensor data 134 through the open riser 24 and near sensor data 134 for an edge 26 of a stair 20. In other words, when the sensor 132 cannot see the riser 24, the edge 26 for the treads 22 of the stairs 20 may appear to the robot 100 as floating rungs and may be falsely identified as an obstacle of the robot 100 by the robot's perception system 180. When a robot 100 is about to descend or descending a set of stairs 20, a sensor 132, such as a stereo camera, may produce poor sensor data 134 due to the repetitive structure and lines that define a staircase. For example, stereo cameras specifically function by trying to find a portion of two different images that are the same object in the real world and use parallax to determine a distance for that object. Yet based on the repeating lines of a staircase when viewing it from top to bottom, sensors 132 are more likely to mismatch the same object and thus generate poor sensor data 134. This is particularly common for industrial or grated staircases because the grating introduces more repeating lines that the sensor 132 is capable of mismatching. Although not all staircases are grated, this presents a problem to the navigation of the robot 100 because robots 100 may often be deployed in industrial environments 10. Though these scenarios do not occur for every type of staircase, a robot 100 that struggles to ascend one type of staircase and to descend another may limit the robot's versatility and robustness.

[0050] To attempt to address some of these sensor data issues, the robot 100 uses a system called stair tracker 200 for detecting and tracking features for stairs 20. Stair tracker 200 allows the robot 100 to understand ambiguous data by having a lower dimensional model. Referring to FIGS. 2A and 2B, in some implementations, the stair tracker 200 is configured to receive sensor data 134 and output a stair model 202. The model 202 may include some form of a floor height and a series of stairs 20. Here, a stair 20 is a line segment with a direction, a location, and an extent in either direction. The model 202 may generally assume the stairs 20 are horizontally constrained and include a minimum/maximum rise and a minimum/maximum run. Alternatively, the slope may be constrained to a minimum/maximum value.

[0051] To generate the model 202, the stair tracker 200 includes a detector 210 and a detection tracker 220. The detector 210 of the stair tracker 200 receives the sensor data 134 from the sensor system 130 and generates a detected feature 212. This detected feature 212 may correspond to different structural features of the stairs 20 such as edges 26, treads 22, risers 26, walls 28, and/or some combination thereof. As the robot 100 approaches a set of stairs 20, the detector 210 functions to determine a detected feature 212 (e.g., shown in FIG. 2B as a detected edge 212, 212_e) corresponding to a feature of the stairs 20 (e.g., an edge 26

of a first stair 20). The detector 210 generates the detected feature 212 at a particular time t_i. Once the detector 210 determines the detected feature 212 at the particular time t_i, the detection tracker 220 monitors that this detected feature 212_e remains the best representation of the actual feature for the stairs 20 during future time steps t_{i+1}. In other words, the stair tracker 200 is receiving sensor data 134 at a particular frequency as the sensor system 130 captures the sensor data 134. The detector 210 determines the detected feature 212 at a first time step t₁ based on both sensor data 134 from the first time step t₁ and aggregate sensor data 134 from prior time steps t_{i-1}. The detector 210 communicates the detected feature 212 to the detection tracker 220 and the detection tracker 220 establishes the detected feature 212 as a tracked detection 222 (also referred to as a primary detection) or initial detection when no primary detection exists at the detection tracker 220. In other words, when the detection tracker 220 is not tracking the stair feature corresponding to the detected feature 212 received from the detector 210, the detection tracker 212 initializes a tracking process for this stair feature using the detected feature 212 at the first time step t₁. For instance, FIG. 2B illustrates the detection tracker 220 identifying the first detected feature 212, 212_e₁ for an edge 26 of a stair 20 at the first time step t₁ as the tracked detection 222. At a second time step t₂ subsequent to the first time step t₁, the stair tracker 200 receives sensor data 134 generated at the second time step t₂ and/or during a time period between the first time step t₁ and the second time step t₂ as the most recent sensor data 134. Using the most recent sensor data 134, the detector 210 generates another detected feature 212 at a later time t_{i+1}. For example, the detector 210 generates a second detected feature 212, 212_e₂ for the edge 26 of the stair 20 at the second time step t₂.

[0052] To perform its tracking process, when the detection tracker 220 receives the second detected feature 212, 212₂, the detection tracker 220 determines whether the second detected feature 212₂ received at the second time step t₂ is similar to the first detected feature 212₁ from the first time step t₁ (now the tracked detection 222). When the first and the second detected features 212 are similar, the detection tracker 220 merges the first and the second detected features 212 together to update the tracked detection 222. Here, during a merging operation, the detection tracker 220 may merge detected features 212 together with the tracked detection 222 using averaging (e.g., a weighted average weighted by a confidence error in the detected feature 212). When the second detected feature 212₂ is not similar to the first detected feature 212₁, the detection tracker 220 determines whether an alternative tracked feature 224 exists for the stair feature corresponding to the second detected feature 212₂ (i.e., has the detection tracker 220 previously identified at detected feature 212 as an alternative tracked feature 224). When an alternative tracked feature 224 does not exist, the detection tracker 220 establishes the second detected feature 212₂ at the second time step t₂ to be the alternative tracked feature 224. When an alternative tracked feature 224 already exists, the detection tracker 220 determines whether the second detected feature 212₂ at the second time step t₂ is similar to the existing alternative tracked feature 224. When the second detected feature 212₂ at the second time step t₂ is similar to the existing alternative tracked feature 224, the detection tracker 220 merges the second detected feature 212₂ at the second time step t₂ with the existing alternative tracked feature 224 (e.g., using averaging or weighted

averaging). When the second detected feature **212₂** at the second time step **t₂** is not similar to the existing alternative tracked feature **224**, the detection tracker **200** may generate another alternative tracked feature **224** equal to the second detected feature **212₂** at the second time step **t₂**. In some examples, the detection tracker **220** is configured to track and/or store multiple alternative detections **224**.

[0053] By using the tracking process of the detection tracker **220** in conjunction with the detector **210**, the stair tracker **200** may vet each detection to prevent the stair tracker **200** from detrimentally relying on a detection. In other words, with the robot **100** constantly gathering sensor data **134** about itself (e.g., at a frequency of 15 Hz), a reliance on a single detection from a snapshot of sensor data **134** may cause inaccuracy as to the actual location of features of the stairs **20**. For example, a robot **100** may move or change its pose **P** between a first time and a second time generating sensor data **134** for areas of the stairs **20** that were previously occluded, partially occluded, or poorly captured in general. Here, a system that only performed a single detection at the first time may suffer from incomplete sensor data **134** and inaccurately detect a feature. In contrast, by constantly tracking each detection based on the most recent sensor data **134** available to the stair tracker **200** over a period of time, the stair tracker **200** generates a bimodal probability distribution for a detected stair feature (e.g., a primary detection and an alternative detection). With a bimodal probability distribution for a feature of a stair **20**, the stair tracker **200** is able to generate an accurate representation for the feature of the stair **20** to include in the stair model **202**. Furthermore, this detection and tracking process tolerates a detection at any particular instance in time that corresponds to arbitrary poor sensor data **134** because that detection is tracked and averaged over time with other detections (e.g., presumably detections based on better data or based on a greater aggregate of data over multiple detections). Therefore, although a single detection may appear noisy at any moment in time, the merging and alternative swapping operations of the detection tracker **220** develop an accurate representation of stair features over time.

[0054] These stair features may then be incorporated into the stair model **202** that the stair tracker **200** generates and communicates to various systems of the robot **100** (e.g., systems that control the robot **100** to traverse the stairs **20**). In some configurations, the stair tracker **200** incorporates a tracked feature **222** into the stair model **202** once the tracked feature **222** has been detected by the detector **210** and tracked by the detection tracker **220** for some number of iterations. For example, when the detection tracker **220** has tracked the same feature for three to five detection/tracking cycles, the stair tracker **200** incorporates the tracked detection **222** (i.e., a detection that has been updated for multiple detection cycles) for this feature into the stair model **202**. Stated differently, the stair detector **200** determines that the tracked detection **222** has matured over the detection and tracking process into a most likely candidate for a feature for the stairs **20**.

[0055] When a sensor **132** peers down a set of stairs **20**, this descending vantage point for a sensor **132** produces a different quality of sensor data **134** than a sensor **132** peering up a set of stairs **20**. For example, peering up a set of stairs **20** has a vantage point occluding the treads **22** of stairs **20** and some of the riser **26** while peering down the set of stairs

20 has a vantage point that occludes the risers **26** and a portion of the treads **22**. Due to these differences among other reasons, the stair tracker **200** may have separate functionality dedicated to stair ascent (e.g., a stair ascent tracker **200a**) and stair descent (e.g., a stair descent tracker **200b**). For example, each stair tracker **200a-b** may be part of the stair tracker **200**, but separate software modules. In some configurations, each stair tracker **200a-b**, though a separate model, may coordinate with each other. For instance, the stair ascent tracker **200a** passes information to the stair descent tracker **200b** (or vice versa) when the robot **100** changes directions during stair navigation (e.g., on the stairs **20**).

[0056] Referring to FIGS. 2C-2I, the stair ascent tracker **200a** includes a detector **210**, **210a** and a detection tracker **220**, **220a**. Here, the detector **210a** and the detection tracker **220a** have functionality as previously described such that the detector **210a** is configured to detect a feature of one or more stairs **20** (e.g., an edge **26** or a wall **28**) and the detection tracker **220a** is configured to track the detected feature **212** to ensure that the detected feature **212** remains an accurate representation of the actual feature of the stair **20** based on the modeling techniques of the stair ascent tracker **200** and current sensor data **134** captured by the robot **100**. Yet in some examples, the detector **210a** and the detection tracker **220a** also include additional or alternative operations specific to ascending a set of stairs **20**.

[0057] In some examples, such as FIGS. 2D-2F, the detector **210a** is configured to detect an edge **26** of a stair **20**. Generally speaking, to identify sensor data **134** that may correspond to the edge **26** of a stair **20**, the detector **210a** may first identify a location of a previous stair **20** based on prior detections. In other words, the detector **210a** identifies sensor data **134** corresponding to a second stair **20**, **20b** based on a location of sensor data **134** previously detected for a first stair **20**, **20a**. In this approach, the detector **210a** is able to bootstrap itself up any number of stairs **20** while also adapting to changes in a previous stair rather than a world frame. By looking at sensor data **134** relative to sensor data **134** of a prior stair **20**, the relativity allows the detector **210** to detect features even if these features are changing over the course of a staircase (e.g., the stairs **20** are winding). For example, FIG. 2D depicts that the sensor data **134** for the second stair **20b** exists in a detection area **A_D** shown as a dotted rectangular target detection box relative to a first detected edge **212**, **212e₁** of the first stair **20a**.

[0058] Referring to FIG. 2E, in some implementations, based on the sensor data **134** within the detection area **A_D**, the detector **210a** divides the detection area **A_D** into segments (e.g., columnar segments defining a pixel-wide detection column) and traverses each segment of the detection area **A_D** incrementally. When searching a segment of the detection area **A_D** in a direction **D** toward the robot **100** (e.g., a direction towards where an actual edge **26** of the stair **20** would likely exist), the detector **210a** identifies points of sensor data **134** that are the furthest in this direction **D** within the segment of the detection area **A_D**. In some examples, to determine the furthest points in the search direction **D**, the detector **210a** searches each segment of the detection area **A_D** sequentially until a search segment is an empty set and identifies one or more points in the search segment prior to the empty set as one or more points along an edge **26** of the stair **20**. For example, one or more points with a greatest

height (e.g., z-coordinate height) within the search segment correspond to edge points (e.g., shown in red).

[0059] Referring to 2F, in some configurations, the detector **210a** generates a first line L_1 by applying a linear regression fit to the edge points identified by the detector **210a**. For instance, the detector **210a** generates the first line L_1 using a least squares fit. The detector **210a** may further refine this fit due to the fact that some points may correspond to outlier data or points near the extent of the field of view F_p . For example, the detector **210** in FIG. 2F removes the sensor data **134** in the red and purple circles during refinement of the first fit. Here, the detector **210a** may also refine the first fit by determining where the detected stair edge likely ends (or terminates) based on the distribution of sensor data **134** (e.g., shown in green spheres) and removes this sensor data **134**. After one or more of these refinements, the detector **210a** may generate a second line L_2 by applying a linear regression fit to the remaining edge points. Here, the linear regression fit may also be a least squares fit similar to the first line L_1 . In some configurations, after generating the first line L_1 or the second line L_2 , the detector **210** may reject the current detected edge **212e** by comparing it to one or more previously detected edges **212e** and determining, for example, that the current detected edge **212** is too short, too oblique, or embodies some other anomaly justifying rejection. If the detector **210** does not reject the current detected edge **212**, the detector **210a** passes the current detected edge **212e** to the detection tracker **220a** in order for the detection tracker **220a** to perform the tracking process.

[0060] Unlike the detection for features of other stairs **20**, detection for the first stair **20**, **20a** of a staircase may be unique in that the detector **210a** does not know where to look for sensor data **134**. In other words, referring back to FIG. 2D, the detector **210a** identified potential points of the sensor data **134** that would likely correspond to a feature for detection of the second stair **20b** based on a previously detected feature **212** of the first stair **20a**. When performing detection on the first stair **20a**, the detector **210a** does not have this prior stair reference point. To find the first stair **20a**, the detector **210a** is configured to classify the sensor data **134** according to height (i.e., a z-coordinate) along a z-axis A_z (e.g., parallel to a gravitational axis of the robot **100**). For instance, in FIG. 2G, the classifications C may include a floor height classification C , C_F , an expected first stair classification C , C_{S1} , and/or an expected second stair classification C , C_{S2} . In some examples, the detector **210a** first classifies the sensor data **134** by the floor height classification C_F based on an assumption that the feet **124** of the robot **100** are on the floor. The detector **210a** may generate the other classifications C relative to the determined floor height. Here, the detector **210a** uses its prior knowledge of how tall stairs/staircases are typically in the real world to define the classification heights of the first and second stairs relative to the floor height.

[0061] In some configurations, based on the classifications C , the detector **210a** searches a detection area A_D as shown with respect to FIG. 2E to determine edge points of the sensor data **134**. In other words, to detect the edge points for the first stair **20a** from the sensor data **134**, the detector **210a** performs the column search described with respect to FIG. 2E at a height assumed to correspond to a first stair **20a** (e.g., based on height corresponding to the expected first stair classification C , C_{S1}). In some examples, the detector **210a** is configured to cluster the edge points and to merge any

clusters CL that may seem likely to be part of the same stair **20** except for a gap between the clusters CL. In some implementations, with identified and clustered edge points, the detector **210** determines whether the identified and clustered edge points indicate a consistent relationship between the sensor data **134** classified as a first stair classification C_{S1} and a second stair classification C_{S2} . Here, the identified and clustered edge points may indicate a consistent relationship between the sensor data **134** classified as a first stair classification C_{S1} and a second stair classification C_{S2} when the identified and clustered edge points delineate the stair classifications C_{S1} , C_{S2} and define a second set of edge points above a first set of edge points (e.g., reflective of an actual staircase where one stair is above another). When this occurs, the stair ascent tracker **200a** may determine that the underlying sensor data **134** is most likely to correspond to a staircase and apply itself (or recommend its application) to the underlying sensor data **134** to detect features.

[0062] Based on the sensor data classification process, the detector **210a** is aware of an approximate location for the first stair **20**, **20a**. Using this approximate location, the detector **210a** may refine the height of a stair **20** (e.g., the first stair **20a**). For instance, the detector **210a** selects points of the sensor data **134** that likely correspond to the tread **22** of a stair **20** based on the approximate location and averages the heights of the selected points of the sensor data **134**. Here, the detector **210a** then defines the average height of the selected points to be a refined height of the tread **22** of the stair **20** (i.e., also referred to as a height of the stair **20**). The detector **210a** may perform this height refinement when the robot **100** is near to the stair **20** such that the sensor(s) **132** of the robot **100** are above the stair **20**.

[0063] Referring to FIG. 2H, the detector **210a** is configured to generate a detected wall **212**, **212w** as a detected feature **212**. In some examples, to detect a wall **28**, the detector **210a** first estimates an error boundary E_b for a detected edge **212e** for one or more stairs **20** to define a search region (i.e., a detection area A_D) for a wall **28**. Here, the error boundary refers confidence tolerance for the detected edge **212e**. The error boundaries are generally smaller closer to the robot **100** (i.e., a tighter confidence tolerance for an edge **26**) and larger further away from the robot **100** (i.e., a looser confidence tolerance for an edge **26**). The detector **210a** estimates the error boundary E_b because the detector **210a** wants to avoid accidentally including an edge point as a wall point during detection. In FIG. 2H, the detector **210a** estimates an error boundary E_b for each stair **20** (e.g., shown as a first stair **20a** and a second stair **20b**) in a first direction (e.g., shown as a first error boundary $E_{b_{a1}}$ along an x-axis) and a second direction (e.g., shown as a second error boundary $E_{b_{a2}}$ along the z-axis). The detector **210a** then defines the search area or detection area A_D as an area bound at least partially by the error boundaries E_b . For example, a first detection area A_{D1} spans the error boundary E_b from the first stair **20a** to the error boundary E_b from the second stair **20b** to search for one or more walls **28** intersecting the extents of the first stair **20a** and a second detection area A_{D2} spans the error boundary E_b from the second stair **20b** to the error boundary E_b from a third stair **20c** (partially shown) to search for one or more walls **28** intersecting the extents of the second stair **20a**. By using this error boundary approach, the detector **210a** attempts to

prevent confusing parts of an edge **26** that are noisy sensor data **134** with a wall detection **212w**.

[0064] Referring to FIG. 2I, in some implementations, the detector **210a** searches the detection area A_D outward from a center of the staircase (or body **110** of the robot **100**). While searching the detection area A_D outward, the detector **210a** determines a detected wall **212w** when the detector **210a** encounters a cluster CL of sensor data **134** of sufficient size. In some examples, the cluster CL of sensor data **134** is of sufficient size when the cluster CL satisfies an estimated wall threshold. Here, the estimated wall threshold may correspond to a point density for a cluster CL. When the detector **210a** identifies a cluster CL of sensor data **134** satisfying the estimated wall threshold, the detector **210a** estimates that a wall **28** is located at a position at an inner edge (i.e., an edge towards the center of the staircase) of the cluster CL. Here, the detector **210a** defines the estimated wall location as a detected wall **212w**. For instance, in FIG. 2I, the detector **210a** determines a first detected wall **212w₁** and a second detected wall **212w₂** on each side of the staircase corresponding to an inner edge of a first cluster CL, CL₁ and a second cluster CL₂, respectively. In some configurations, the detector **210a** also generates an error boundary about the detected wall **212w** based on a density of the sensor data **134** at the corresponding cluster CL.

[0065] Referring to FIGS. 2J-2U, the stair tracker **200** may be configured as a stair descent tracker **200**, **200b** that includes additional or alternative functionality to the ascent stair tracker **200a** or general stair tracker **200**. Here, the functionality of the descent stair tracker **200b** is specific to the scenario where the robot **100** descends the stairs **20** and how the robot **100** perceives sensor data **134** during descent. When descending the stairs **20**, one or more sensors **132** may generate inaccurate sensor data **134** due to particular limitations of the sensors **132**.

[0066] Additionally, in some examples, during descent of a staircase, the robot **100** descends the stairs **20** backwards. In other words, the robot **100** is oriented such that the hind legs **120c-d** of the robot **100** descend the stairs **20** first before the front legs **120a-b** of the robot **100**. When descending the stairs **20** backwards, the robot **100** may include fewer sensors **132** at the rear of the robot **100** (e.g., about an end of the body **110** near the hind legs **120c-d**) because the robot **100** may be designed to generally frontload the sensor system **130** to accommodate for front-facing navigation. With fewer sensors **132** at the rear end of the robot **100**, the robot **100** may have a limited field of view F_V compared to a field of view F_V of the front end of the robot **100**.

[0067] For a descending staircase, most of the staircase may not be in the field of view F_V of the robot **100** until the robot **100** is close or adjacent to the staircase. Since the staircase is not within the field of view F_V of the robot **100** earlier, the robot **100** is without much initial sensor data **134** about the descending staircase before the robot **100** is at the top of the stairs **20**. Accordingly, the robot **100** uses the stair descent tracker **200b** to recognize the descending staircase according to a floor edge **26**, **26f** that corresponds to an edge **26** of a top stair **20** of the staircase. In some examples, in order to determine the floor edge **26f**, the stair descent tracker **200b** is configured to determine a location where the support surface **12** for the robot **100** (i.e., also referred to as the floor **12** beneath the robot **100**) disappears in a straight line. In other words, the robot **100** determines that the straight line corresponding to where the support surface **12**

disappears may be the floor edge **26f** (i.e., the edge **26** of the top stair **20** of a descending set of stairs **20**).

[0068] The stair descent tracker **200b** includes a detector **210**, **210b** and a detection tracker **220**, **220b**. Here, the detector **210b** and the detection tracker **220b** of the stair descent tracker **200b** may behave in similar ways to the detector **210** and the detection tracker **210** of the stair tracker **200** and/or stair ascent tracker **200a**. Namely, the detector **210b** is configured to detect a feature of one or more stairs **20** (e.g., an edge **26** or a wall **28**) and the detection tracker **220b** is configured to track the detected feature **212** to ensure that the detected feature **212** remains an accurate representation of the actual feature of the stair **20** based on the modeling techniques of the stair descent tracker **200** and current sensor data **134** captured by the robot **100**.

[0069] In some implementations, the detector **210b** of the stair descent tracker **200b** receives the sensor data **134** from the sensor system **130** and generates a detected feature **212**. As the robot **100** approaches a descending set of stairs **20**, the detector **210b** functions to determine a detected edge **212**, **212e** corresponding to a floor edge **26f**. Once the detector **210b** determines the detected edge **212e**, the detection tracker **220b** monitors that this detected edge **212e** remains the best representation of the floor edge **26f** during future time steps.

[0070] Referring to FIGS. 2K-2P, in some configurations, the detector **210b** of the stair descent tracker **200b** performs further processing on the received sensor data **134** in order to generate a detected edge **212**, **212e** as the detected feature **212**. For example, the detector **210b** receives the sensor data **134** and classifies the sensor data **134** by height. Here, the height of a point of the sensor data **134** corresponds to a height in the Z-axis (i.e., an axis parallel to the gravitational axis of the robot **100**). In some examples, the classification process by the detector **210b** classifies each point of the sensor data **134** as a height classification C corresponding to either a height of the floor C, C_F about the robot **100**, a height above the floor C, C_{AF} , or a height below the floor C, C_{BF} . Unfortunately, the sensor data **134** may often have gaps or sections missing from the sensor data **134** due to how the environment **10** is sensed or the capabilities of a sensor **132**. To aid further processing by the detector **210b**, the detector **210b** may perform a morphological expand to fill in gaps within the sensor data **134**. For example, a dilate process identifies gaps within the sensor data **134** and fills the identified gaps by expanding sensor data **134** adjacent to the identified gaps.

[0071] With classified sensor data **134**, the detector **210b** may be further configured to perform further processing on the two dimensional image space based on the three dimensional sensor data **134** (e.g., as shown in FIG. 2L). In the two dimensional image space, each pixel P_x of the image space may represent or correspond to the height classifications C for the sensor data **134**. In other words, for each pixel P_x , the detector **210b** determines whether the classified sensor data corresponding to a respective pixel position in the image space has been classified as a floor classification C_F , an above the floor classification C_{AF} , or a below the floor classification C_{BF} . With an image space representing the sensor data **134**, the detector **210b** may determine the detected edge **212e** by analyzing pixels P_x of the image space.

[0072] In some examples, such as FIG. 2M, once the detector **210b** associates height classifications with pixels P_x

of an image space, the detector **210b** is configured to search the image space to identify potential pixels P_x that may correspond to the floor edge **26e**. In some implementations, the detector **210b** uses a search column of some predefined width (e.g., a pixel-wide column) to search the image space. For instance, the image space is divided into columns and, for each column, the detector **210b** searches for a change in the height classifications C between pixels P_x . Stated differently, during the search, the detector **210b** identifies a pixel P_x as a floor edge pixel P_x , P_{x_f} when the pixel P_x corresponds to a floor classification C_F that is followed by subsequent pixels P_x corresponding to either missing sensor data **134** or some threshold amount of below-floor sensor data **134** (i.e., with below the floor classifications C_{BF}). In some configurations, the detector **210b** performs the column-wide search starting at a bottom of the image space where the pixels P_x include floor classifications C_F and searching upwards in a respective column.

[0073] By analyzing an image space to determine the detected edge **212e**, the detector **210b** may avoid potential problems associated with searching sensor data **134** in three dimensional space. For instance, when the detector **210b** attempts to detect the floor edge **26f**, the sensor data **134** may appear to be in an alternating height pattern of high-low-high-low (e.g., where high corresponds to a floor classification C_F and low corresponds to a below floor classification C_{BF}). Yet in one configuration of the sensor data **134**, the floor edge **26f** is actually located within the first group of high sensor data **134**, but the third group of high sensor data **134** may confuse the detector **210b** causing the detector **210b** to interpret that the floor edge **26f** exists in the third group of high sensor data **134**. In a contrasting configuration of sensor data **134** with the same pattern, the floor edge **26f** may actually exists in the third group of high sensor data **134**, but the second group of low sensor data **134** between the first group and the third group may confuse the detector **210b** causing the detector **210b** to detect the floor edge **26f** in the first group of high sensor data **134**. Because the sensor data **134** may have these inconsistencies, feature detection by the detector **210b** may occur in two dimensional space instead of three dimensional space.

[0074] As shown in FIGS. 2N and 20, when the detector **210b** completes the search of the image space and identifies floor edge pixels P_x , P_{x_f} , the detector **210b** may then approximate the floor edge **26f** by performing one or more linear regression fits to the identified floor edge pixels P_x , P_{x_f} . In some examples, the detector **210b** clusters the floor edge pixels P_{x_f} prior to applying a linear regression fit. For example, FIG. 2N depicts three clusters of flood edge pixels P_{x_f} . Here, this clustering technique may help more complex situations where the detector **210b** needs to merge together identified floor edge pixels P_x , P_{x_f} to provide some linearity to the identified floor edge pixels P_x , P_{x_f} . In some implementations, such as FIG. 2O, the detector **210b** first defines the floor edge **26f** as a first line L_1 associated with a least squares fit and then refines the first line L_1 from the least squares fit by identifying outlier floor edge pixels P_x , P_{x_f} and removing these outliers. For instance, the detector **210b** identifies outlier floor edge pixels P_{x_f} near the periphery of the field of view F_V and, as illustrated by comparing FIGS. 2N and 2O, the detector **210b** removes these outlier floor edge pixels P_{x_f} . With outliers removed, the detector **210b** applies a refined fitting to generate a second line L_2 to represent the floor edge **26f**. In some examples, the second

line L_2 does not use a least squares fit (e.g., a fit based on Ridge regression), but uses a fit based a minimization of an absolute value for a loss function (e.g., a fit based on Lasso regression). By using a second line L_2 with a fit based on, for example, Lasso regression, the detector **210b** may fit the line L to more appropriately reflect where portions of the sensor data **134** appear to accurately define the floor edge **26f** (e.g., a cluster of floor classifications C_F in close proximity to a cluster of below floor classifications C_{BF} or narrow gaps between sensor data **134**) while other portions of the sensor data **134** lack accurate definition of the floor edge **26f** (i.e., is missing data and has large perception gaps for the 3D space about the robot **100**). In comparison, a least squares fit line generally does not account for these nuances and simply constructs the line L through the middle of gaps of missing data **134**. In other words, a least squares fit line can be more influenced by outliers than a fit based on a minimization of an absolute value for a loss function.

[0075] In some examples, the detector **210b** determines an error **216** or an error value to indicate an accuracy (or confidence) of the detected edge **212e** with respect to an actual edge **26** (e.g., a floor edge **26f**). Here, to determine the error **216**, the detector **210b** may use, as inputs, the number of points (e.g., the number of identified floor edge pixels P_{x_f}) used to construct the line L , a measurement of a distance between the floor and points of the generated line L (i.e., a size of gap between the floor **12** and the generated line L), and/or the fit of the line L (i.e., a metric representing the consistency of points on the line L). In some implementations, the error **216** indicates both a distance error and a rotation error (e.g., a yaw error). Here, in FIG. 2P, the detector **210b** depicts ordered distance bars a visual illustration of the error computing process.

[0076] The detector **210b** is configured to communicate the detected feature **212** (e.g., the detected edge **212e**) to the detection tracker **220b** of the stair descent tracker **200b**. Here, the detection tracker **220b** performs the tracking process for the detected feature **212** similar to the tracking process described with respect to FIG. 2B. In some examples, the detection tracker **220b** uses the error **216** calculated by the detector **210b** during the merging operation of the tracking process. For example, when merging a detected feature **212** at a first time step t_1 with a subsequent detected feature **212** at a second time step t_2 , the detection tracker **220b** performs a weighted average of the detected features **212** where the weights correspond to the error valve **216** of each detected feature **212**. Additionally, the error **216** associated with a detected feature **212** may also be used to determine whether the tracked detection **222** should be replaced by the alternative tracked feature **224**. In other words, when the error **216** for the alternative tracked feature **224** satisfies a tracking confidence threshold, the detection tracker **220b** replaces the tracked detection **222** with the alternative tracked feature **224**. Here, the tracking confidence threshold may refer to a difference value between two errors **216** (e.g., a first error **216** for the tracked detection **222** and a second error **216** for the alternative tracked feature **224**).

[0077] To generate the staircase model **202**, the detector **210b** is also configured to detect the walls **28** about a set of stairs **20** as a detected feature **212**. When using the stair descent tracker **200b** to detect walls **28** about the set of stairs **20**, in some examples, such as FIG. 2Q, the detector **210a** defines regions where a wall **28** may exist. For example, the

detector **210b** is aware that walls **28** do not intersect the robot **100** (e.g., the body **110** of the robot **100**) and that walls **28** do not exist in a foot step of the robot **100** (e.g., based on perception systems **180** of the robot **100**). Accordingly, the detector **210b** may limit its detection to areas within the sensor data **134** to regions that exclude the robot **100** and footstep location. In some examples, to detect walls **28**, the detector **210b** searches defined regions outward from a center (e.g., outward from a body **110** of the robot **100**).

[0078] While searching outward, the detector **210b** establishes a scoring system for the sensor data **134**. Here, the scoring system counts each point of data for the sensor data **134** in a horizontal or radial distance from the robot **100** (e.g., a distance in the XY plane or transverse plane perpendicular to the gravitational axis of the robot **100**). For each search region (e.g., every centimeter), the scoring system adds a count to a score for each point of sensor data **134** within the search region. As the detector **210b** moves to the next search region further from the robot **100**, the detector **210b** discounts the score proportionally to the distance from the robot **100**. For example, when the search area is a square centimeter, at a distance of two centimeters from the robot **100** in a second search region, the detector **210b** subtracts a count from the score (i.e., the distance discount), but proceeds to add a count from each point of the sensor data **134** in this second search area. The detector **210b** may iteratively repeat this process for the field of view F_V to determine whether walls **28** exist on each side of the robot **100**. In some configurations, the detector **210b** detects that a wall **28** exists (i.e., determines a detected feature **212**, **212w** for the wall **28**) when the score satisfies a predetermined score threshold. In some examples, the detector **210b** establishes error bounds $E_{b,1,2}$ based on a value of 0.5 to 2 times the score threshold. Once the detector **210b** generates a detected wall **212w** at a particular time step t_i , the detector **210b** passes this detected feature **212** to the detection tracker **220b** to perform the tracking process on this wall feature.

[0079] Additionally or alternatively, when using the stair descent tracker **200b**, the detector **210b** determines a width of a stair **20** within a set of stairs **20** and assumes that this width is constant for all stairs **20** within the set. In some configurations, the detector **210b** searches the sensor data **134** in one horizontal direction and, based on a detected wall **212w** in this horizontal direction and a known position of the robot **100**, the detector **210b** presumes a location of a detected wall **212w** for an opposite wall **28**. These approaches may be in contrast to the stair ascent tracker **200a** that identifies a width on each end of a stair **20**.

[0080] Referring to FIGS. 2R-2U, besides detecting the floor edge **26f** and one or more walls **28** (i.e., lateral boundaries for the robot **100**), the detector **210b** is able to detect stairs **20** or stair features of the staircase (e.g., as the robot **100** descends the stairs). That is, here, stair features refer to features of the stairs **20** that exclude features of the floor (e.g., a floor edge **26f**) and features of the wall(s) **28** (e.g., treads **22**, risers **24**, edges **26**, etc.). In some examples, the detector **210b** is configured to detect features of stairs **20** after first performing detection with respect to the floor edge **26f** (i.e., the starting point and reference line for descending a staircase) and detection of one or more walls **28** surrounding the staircase. By performing detection of stair features after detection of one or more walls **28**, the detector **210b** excludes the locations of wall(s) **28** from its detection area A_D when detecting these stair features. For instance, the

detector **210b** filters out the sensor data **134** previously identified as likely corresponding to a wall **28**.

[0081] In some examples, the detector **210b** clusters the sensor data **134** based on a single dimension, a z-coordinate corresponding to a height position of a point within the sensor data **134**. As stated previously, the height or z-coordinate refers to a coordinate position along the z-axis A_z (i.e., parallel to the gravitational axis of the robot **100**). In order to cluster the sensor data **134** based on a height position, the detector **210b** orders points of the sensor data **134** based on height, identifies peaks within the height order (e.g., convolves with a triangular kernel), and groups the points of the sensor data **134** based on the identified peaks. In other words, when ordering the points of the sensor data **134** based on height, the detector **210b** recognizes there are bands of height ranges (e.g., corresponding to the discrete height intervals of the structure of a staircase). In a staircase with three stairs **20**, the height ranges may correspond to a first tread height of a first stair **20**, **20a**, a second tread height of a second stair **20**, **20b**, and a third tread height of a third stair **20**, **20c**. By identifying these height increments or peaks, the detector **210** is able to cluster the points of sensor data **134**. The detector **210b** may merge the clusters **C1** as needed to refine its grouping of a cluster **C1**. In some configurations, the height clusters **C1** undergo the same detection and tracking process as other detected features **212**.

[0082] In some implementations, a cluster **C1** also includes a cluster confidence indicating a confidence that a height of a respective cluster corresponds to a stair **20** (e.g., a tread **22** of a stair **20**). For instance, in FIG. 2R, each cluster **C1** is visually represented by a sphere with a diameter or size that indicates the detector's confidence in the cluster **C1**. In some configurations, the confidence in the cluster **C1** is based on a number of points in the cluster **C1** (e.g., statistically increasing the likelihood the height correctly corresponds to a stair **20**). As an example, FIG. 2R illustrates that the detector **210b** is less confident in the third cluster **C1**, **C1₃** than the other clusters **C1** due to the diameter of the third cluster **C1₃** represented as smaller than the other clusters **C1**. When the robot **100** is descending the stairs **20** as the stair descent tracker **200b** operates, the detector **210b** may include footstep information **FS**, **FS₁₋₄** that identifies a location where the robot **100** successfully stepped on the staircase. By including footstep information **FS**, the detector **210b** may refine its cluster confidences. In other words, since stairs **20**, by nature, occur at discrete height intervals, a successful footstep **FS** means that a cluster **C1** at or near that footstep height is correct; resulting in the detector **210b** significantly increasing the confidence associated with the cluster **C1**. For example, with a first footstep **FS**, **FS₁** at a first stair **20**, **20a** and a second footstep **FS**, **FS₂** at a second stair **20**, **20b**, the detector **210b** may determine a height interval between the first stair **20a** and the second stair **20b** and apply this interval to the clusters **C1** to update the cluster confidences. For instance, the detector **210b** increases the cluster confidence for a cluster **C1** that exists at a height that is an integer multiple of the height interval between the first stair **20a** and the second stair **20b**. In some examples, the detector **210b** only increases the confidence for a cluster **C1** when the cluster **C1** occurs at or near a location where the robot **100** successfully steps on a stair **20** of the staircase. **[0083]** When detecting stair features, the detector **210b** may detect an edge **26** of a single stair **20** as a detected features **212** much like it detected the floor edge **26f**. In other

words, the detector **210b** may classify sensor data **134** or clusters **C1** of sensor data **134** as a stair tread **C**, **C_T** (like a floor classification **C_F**) and below the stair tread **C**, **C_{BT}** (like a below floor classification **C_{BF}**). Here, FIG. 2T illustrates sensor data **134** that has been classified as a stair tread classification **C_T** and a below the stair tread classification **C_{BT}**. Based on the classifications of sensor data **134** related to a tread **22** of a stair **20**, the detector **210b** may be configured to perform a one-dimensional search or a two dimensional search (e.g., like the detection of the floor edge) of the classified sensor data to detect the edge **26** of a stair **20**. When the detector **210b** performs a one dimensional search, the detector **210b** searches the one dimensional height information for the sensor data **134** and assumes that the edge **26** is parallel to the detected floor edge **212**, **212e** previously confirmed by the detection and tracking process of the stair descent tracker **200b** when the robot **100** initially approached the descending stairs **20**. By performing a two-dimensional search and edge detection, unlike a one-dimensional search, the detector **210b** may be able to detect a curved set of stairs **20** with edges **26** that are not necessarily parallel to other edges **26** of stairs **20** within the staircase. In some configurations, the detector **210b** uses a multi-modal or hybrid search approach where the detector **210b** first attempts to generate a detected edge **212**, **212e** for a stair **20** based on a two-dimensional search, but reverts to the one-dimensional search if the sensor data **134** is an issue or if the detector **210b** determines that its confidence for a detected edge **212e** of the two-dimensional search does not satisfy a search confidence threshold.

[0084] One of the differences between ascent and descent is that descent has to often deal with poor sensor data **134** due to the repeating nature of a set of stairs **20**. Quite frequently, the sensor data **134** on, or prior to, descent may be consistently poor over time and with changes in space. Due to a high likelihood of poor sensor data **134**, the detector **210b** is configured to assume that some of the height clusters **C1** correspond to real stairs **20** of the staircase and others do not; while there also may be stairs **20** in the actual staircase that do not correspond to any cluster **C1** of sensor data **134**. Based on these assumptions, the detector **210b** generates all possible stair alignments **AL** for the clusters **C1** identified by the detector **210b**. Here, a stair alignment **AL** refers to a potential sequence of stairs **20** where each stair **20** of the sequence is at a particular height interval that may correspond to an identified cluster **CL**. When generating all possible stair alignments **AL**, the detector **210b** may insert or remove potential stairs from the stair alignment **AL**.

[0085] To illustrate, FIG. 2U depicts that the detector **210b** identified four clusters **C1**, **C1₀₋₃**. Here, there is a large height gap between a first cluster **C₀** and a second cluster **C₁**. As such, the detector **210b** generates alignments **AL** where a potential stair (e.g., depicted as **S**) is located at some height between the first cluster **C₀** and the second cluster **C₁** (e.g., potential stairs shown at a third height **h3**). When evaluating all of the possible alignments **AL**, the detector **210a** may determine whether the potential stairs within an alignment **AL** occur at height intervals with uniform spacing reflective of an actual staircase. In this example, a first alignment **AL**, **AL₁** with a potential stair at each identified cluster **C1** fails to have uniform spacing between potential stairs corresponding to the first cluster **CL₀** and the second cluster **CL₁**. A second alignment **AL**, **AL₂** does not include a potential stair corresponding to the third cluster **C**, **C₂**, but the

sequence of potential stairs in this second alignment **AL₂** still fails to have a uniform spacing between each potential stair due to the large height gap between the first height **h1** and a fifth height **h5**. For a third alignment **AL**, **AL₃**, the detector **210b** generates a potential stair in the gap between the first cluster **C₀** and the second cluster **C₁** at the third height **h3**, but this third alignment **AL₃** also fails to have a uniform spacing between each potential stair. For instance, the potential stair at a sixth height **h6** has a different spacing between neighboring stairs compared to the potential stair at the third height **h3**. In a fourth alignment **AL**, **AL₄** generated by the detector **210b**, the detector **210b** does not associate a potential stair with the third cluster **CL**, **CL₂** and also generates a potential stair at the third height **h3**. Here, this sequence of potential stairs does have uniform spacing and, as such, the detector **210b** determines that the fourth alignment **AL₄** is the best stair alignment candidate **218** (e.g., as shown by the box around this alignment sequence). In some configurations, the detector **210b** scores each of the alignments **AL** and selects the alignment **AL** with the best score (e.g., highest or lowest score depending on the scoring system) as the best stair alignment candidate **218**. In these configurations, the score may incorporate other detection or tracking based information such as cluster confidence, an amount of points forming a cluster, and/or stair detections previously tracked and confirmed.

[0086] Although FIGS. 2R-2U illustrate a process for the detector **210b** to detect more than one stair **20**, the detector **210** may identify stair features (e.g., edges **26**) intermittently during this multi-stair detection process. When this occurs, these detected features **212** may be passed to the detection tracker **220b** and subsequently incorporated within the stair model **202**. Additionally or alternatively, different operations performed by this multi-stair detection process may be modified or eliminated, but still result in a detected feature **212** by the detector **210b**. For instance, the process occurs to detect a single stair **20** or a portion of a stair **20**. In another example, the detector **210b** does not utilize footstep information **FS**.

[0087] Referring to FIGS. 3A-3E, in some implementations, the robot **100** includes a stair supervisor **300**. Systems of the robot **100** may be able to handle stair traversal in a few different ways. For instance, the robot **100** may navigate stairs **20** according to the perception system **180**, the stair tracker **200** (e.g., in a stair mode), or using the perception system **180** in combination with the stair tracker **200**. Due to these options, the stair supervisor **300** is configured to govern which of these approaches to use and/or when to use them in order to optimize navigation and operation of the robot **100**. Here, use of the stair supervisor **300** may also help minimize particular weaknesses of implementing one option versus another by performing merging operations between maps **182** from the perception system **180** and the stair model **202** from the stair tracker **200**. Generally speaking, the stair supervisor **300** includes a body obstacle merger **310**, a no step merger **320**, a ground height analyzer **330**, and a query interface **340**. In some configurations, one or more of the functions of the stair supervisor **300** may be performed in other systems of the robot **100**. For instance, FIG. 3A depicts the query interface **340** as a dotted box within the control system **170** because its functionality may be incorporated into the control system **170**.

[0088] With continued reference to FIG. 3A, in some configurations, the stair supervisor **300** is in communication

with the control system 170, the perception system 180, and the stair tracker 200. The stair supervisor 300 receives maps 182 from perception system 180 and the stair model 202 from the stair tracker 200. With these inputs, the stair supervisor 300 advises when the control system 170 should use information from the stair tracker 200, information from the perception system 180, or some combination of both to navigate stairs 20. For instance, each merger component 310, 330 of the stair supervisor 300 may be configured to merge aspects of the stair model 202 with one or more maps 182 of the perception system 180 (e.g., forming an enhanced staircase model or enhanced perception map). In some examples, the stair supervisor 300 communicates a resulting merged map to the control system 170 to enable the control system 170 to control operation of the robot 100 based on one or more of these merged maps (e.g., enhanced no step map 332 and/or the enhanced body obstacle map 312). In addition to receiving these merged maps, the control system 170 may also receive the staircase model 202 and the ground height map 182 unmodified from the stair tracker 200 and the perception system 180 respectively.

[0089] Referring to FIG. 3B, in some examples, the body obstacle merger 310 of the stair supervisor 300 is configured to merge the body obstacle map 182c and the staircase model 202 into an enhanced body obstacle map 312. When merging the body obstacle map 182c and the staircase model 202, the body obstacle merger 310 may identify that at a position in a staircase, the staircase model 200 does not indicate the existence of an obstacle while the body obstacle map 182c disagrees and indicates an obstacle. Here, the obstacle identified by the body obstacle map 182c may be incorporated into the enhanced body obstacle map 312 when the identified obstacle satisfies particular criteria 314. When the criteria 314 is not satisfied, the obstacle is not included in the enhanced body obstacle map 312. In this scenario, the concern is that something is on the staircase that is not part of the staircase model 202 and should be avoided during navigation. In some examples, the criteria 314 corresponds to a confidence of the perception system 180 that the obstacle that exists on the stairs 20 satisfies a confidence threshold. In these examples, the confidence threshold may correspond to a confidence that is above average or exceeds a normal level of confidence. In some configurations, the criteria 314 requires that the identified obstacle exist at a particular height with respect to the staircase to indicate that the identified obstacle most likely exists on the staircase. By setting the criteria 314 to require that the identified obstacle be present at a certain height (e.g., a threshold obstacle height), the criteria 314 tries to avoid situations where the perception system 180 is partially viewing the stairs 20 and classifying the stairs 20 themselves incorrectly as obstacles.

The threshold obstacle height may be configured at some offset distance from the heights of the stairs 20 of the staircase. Some other examples of criteria 314 include how many point cloud points have been identified as corresponding to the obstacle, how dense is the sensor data 134 for the obstacle, and/or whether other characteristics within the obstacle resemble noise or solid objects (e.g., fill rate).

[0090] When the perception system 180 identifies a discrepancy between its perception (i.e., mapping) and the staircase model 202 of the stair tracker 200, this discrepancy is generally ignored if the robot 100 is engaged in a grated floors mode. Here, grated floors may cause issues for the sensor(s) 132 of the robot and thus impact perceptions by the

perception system 180. Therefore, if the robot 100 is actively engaged in the grated floors mode, the stair supervisor 300 is configured to trust identifications by the stair tracker 200 rather than the perception system 180 because the stair tracker 200 has been designed specifically for scenarios with poor sensor data 134 such as grated floors.

[0091] Referring to FIG. 3C, in some configurations, the ground height analyzer 320 of the stair supervisor 300 is configured to identify locations in the staircase model 202 that should be overridden by height data of the ground height map 182a. To identify these locations, the analyzer 320 receives the ground height map 182a and searches the ground height map 182a at or near the location of the staircase within the map 182a to determine whether a height for a segment of the ground height map 182a exceeds a height of the staircase in a corresponding location. In some examples, the ground height analyzer 330 includes a height threshold 322 or other form of criteria 322 (e.g., similar to the criteria 314 of the body obstacle merger 310) such that the ground height analyzer 320 determines that a height within the ground height map 182a satisfies the height threshold 322 or other form of criteria 322. In some configurations, when the analyzer 320 identifies a location in the staircase model 202 that should be overridden by height data from the ground height map 182a, the analyzer 320 generates an indicator 324 and associates this indicator 324 with the staircase model 202 to indicate that the staircase model 202 is overridden in that particular location. In some examples, rather than generating an indicator 324 for the particular location within the staircase model 202, the analyzer 320 associates the indicator with a stair 20 of the staircase model 202 that includes the location. Here, the indicator 324 may not include how the staircase model 202 is overridden (e.g., at what height to override the staircase model 202), but simply that the model 202 is in fact overridden (e.g., at some location on a particular stair 20). This indication may function such that the query interface 340 does not need to query both the ground height map 182a and the staircase model 202 whenever it wants to know information about a location. Rather, the query interface 340 may query only the staircase model 202 and, in a minority of instances, be told an override exists; thus having to subsequently query the ground height map 182a. In some implementations, when the analyzer 320 determines a location within the staircase model 202 that should be overridden by height data of the ground height map 182a, the analyzer 320 dilates the feature at this location in order to include a safety tolerance around the precise location of the object/obstacle corresponding to the height data.

[0092] Referring to FIG. 3D, in some examples, the no step merger 330 of the stair supervisor 300 is configured to merge the no step map 182b and the staircase model 202 to form a modified no step map 332. To form the modified no step map 332, the no step merger 330 generates no step regions in the modified no step map 332 corresponding to areas near some features of the staircase model 202. For instance, the no step merger 330 generates no step regions in the modified step map 332 for a particular distance above and below an edge 26 of each stair 20 as well as no step regions within a particular distance of a wall 28.

[0093] Additionally, the no step merger 330 generates no step regions in the modified step map 332 at locations where the staircase model 202 was overridden by the ground height map 182a. For example, the no step merger 330 identifies

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each stair **20** of the staircase model **202** that corresponds to an override O. Based on this determination, the no step merger **330** divides each identified stair **20** into segments or stripes (e.g., vertical columns of a designated width) and determines which stripes include the override O. For example, FIG. 3D illustrates a second stair **20**, **20b** and a fourth stair **20d** of five stairs **20**, **20a-e** each having an override O (e.g., a first override O, **O₁** and a second override O, **O₂**). Each stipe having an override O may then be designated by the no step merger **330** as a no step region. In some examples, the no step merger **330** dilates the no step regions to as a tolerance or buffer to ensure that neither the feet **124** of the robot **100** nor any other part of the structure of the robot **100** accidentally collides with the object.

[0094] In some implementations, such as FIG. 3E, the query interface **340** interfaces between the control system **170**, the perception system **180**, and the stair tracker **200**. For instance, a controller **172** of the control system **170** may ask the query interface **340** what the height is at a particular location on a stair **20**. The query interface **340** in turn communicates a first query **342**, **342a** to the stair tracker **200** inquiring whether the stair tracker **200** has answer for the height at the particular location on the stairs **20** (i.e., whether the staircase model **202** has an answer). Here, the stair tracker **200** may respond no, yes, or yes, but an override O exists for that stair **20**. When the stair tracker **200** responds with a no, the query interface **340** queries the perception system **180** for the height at the particular location on the stairs **20** since the perception system **180** as the default navigation system will inherently have an answer. When the stair tracker **200** responds yes, the stair tracker **200** returns a response with the height at the particular location on the stairs. When the stair tracker **200** informs the query interface **340** that an override O exists on that particular stair **20**, the query interface **340** sends a second query **342**, **342b** to the perception system **180** to identify whether the stair tracker **200** is overridden at the particular location on the stair **20**. When the answer to this second query **342b** is yes, the query interface **340** requests the height from the perception system **180**. When the answer to this second query **342b** is no, the query interface **340** may return to the stair tracker **200** to retrieve the height location. In some examples, the stair tracker **200** is configured to respond yes or no. In these examples, when the stair tracker **200** responds in the affirmative, the query interface **340** further refines the query **342** to ask whether an override O exists for the stair **20** that includes the particular location.

[0095] In some configurations, an operator or user of the robot **100** commands or activates a stairs mode for the robot **100**. When the robot **100** is in the stairs mode, the stair tracker **200** becomes active (i.e., from an inactive state). With an active stair tracker **200**, the stair supervisor **300** may perform its functionality as a set of stairs **20** within the environment becomes detected and tracked. In some implementations, stair tracker **200** is always active (i.e., does not have to become active from an inactive state) and the always active stair tracker **200** determines whether the robot **100** should enter the stairs mode (e.g., utilizing the stair supervisor **300**).

[0096] When the stair tracker **200** is active, the robot **100** may be constrained as to its speed of travel. In some examples, the speed of the robot **100** is constrained to be a function of the average slope or actual slope of a detected staircase. In some implementations, an active stair tracker

200 enables the robot **100** to select a speed limit to match the robot's stride length to a step length for a detected staircase (e.g., generating one footstep per stair step). For example, when stair tracker **200** is active, the control system **170** may be configured to select a controller **172** with a cadence to achieve one footstep per stair step. Additionally or alternatively, when the stair tracker **200** is active, the stair tracker **200** may have an associated specialty stair controller that has been optimized for aspects of speed, cadence, stride length, etc.

[0097] In some examples, the robot **100** engages in obstacle avoidance tuning when the stair tracker **200** is active. For example, when the stair tracker **200** indicates the robot **100** is actually on the staircase, the robot **100** may change the manner in which it performs obstacle avoidance. When an obstacle constraint exists, obstacle avoidance generally occurs based on a straight line along the border of the obstacle. Here, the orientation of this straight line may be significant, especially in a potentially constrained environment such as a staircase. Therefore, when the stair tracker **200** is active and an obstacle on a staircase seems similar to a wall of the staircase, the robot **100** may redefine the orientation for the wall obstacle as parallel to the direction of the staircase (i.e., much like a staircase wall is typically parallel to the direction of the staircase). This makes obstacle avoidance a little bit easier on the stairs **20**.

[0098] In some implementations, when the stair tracker **200** is active, the stair tracker **200** applies or causes the application of stair-specific step-planner constraints. For instance, the step-planner constraints correspond to a soft constraint that tries to prevent the robot **100** from stepping up or down more than one stair **20** at a time relative to a contralateral leg **120**. Here, a soft constraint refers to a constraint that the robot **100** is urged to obey, but is allowed to violate in extreme or significant conditions (e.g., to satisfy a hard constraint). Another form of step-planner constraints may be constraints that identify when it is too late to switch the touchdown location at a given stair **20**. With the simplified geometry of a staircase, the systems of the robot **100** may compute when it is too late to switch a stair touchdown location. To perform this analysis, the robot **100** may use four potential constraints bounding the edges of a stair **20** above and a stair **20** below the current position for a foot **124** of a swing leg **120_{sw}**. At every time step, the robot **100** checks if the swing leg **120_{sw}** is able to clear these four potential constraints based on the current position and velocity of the swing leg **120_{sw}** in conjunction with how much time is remaining before touchdown. If, at a particular time step, it is not possible to clear these four potential constraints, the robot **100** introduces a hard constraint defining that it is too late to change the stair touchdown location.

[0099] Optionally, when the stair tracker **200** is active, the control systems **170** of the robot **100** may provide a form of lane assist such that the robot **100** traverses the center of the staircase. While an operator of the robot **100** uses a remote controller (e.g., with a joystick) to drive the robot **100**, the lane assist feature may function to automatically drive the robot **100** towards the center of the staircase; eliminating some form of potential operator error. However, with lane assist, if the operator is actually supplying an input that drives the robot away from the center, the lane assist yields to these manual controls. For instance, the lane assist feature turns off completely when the user command is in opposition to the lane assist function.

[0100] Stair tracker 200 may also help prevent cliff scraping that occurs when a swing leg 120_{SW} contacts an edge 26 of a stair 20. For example, using solely the perception system 180, the geometry for stairs 20 is rather complex because the perception system 180 uses blocks in three centimeter resolution. When using stair tracker 200 predominantly or in combination with the perception system 180, the stair geometry may be simplified such that control of the swing leg 120_{SW} lifting over a rise 26 and an edge 26 of a stair 20 may be achieved at a threshold distance from the edge 26 of the stair 20 to prevent cliff scraping.

[0101] FIG. 4 is a flow chart of an example arrangement of operations for a method of generating a staircase model. At operation 402, the method 400 receives sensor data 134 for a robot 100 adjacent to a staircase 20. For each stair 20 of the staircase 20, the method 400 performs operations 404a-c. At operation 404a, the method 400 detects, at a first time step t_i, an edge 26 of a respective stair 20 based on the sensor data 134. At operation 404b, the method 400 determines whether the detected edge 212 is a most likely step edge candidate 222 by comparing the detected edge 212 from the first time step t_i to an alternative detected edge 224 at a second time step t_{i+1}. Here, the second time step t_{i+1} occurs after the first time step t_i. At operation 404c, when the detected edge 212 is the most likely step edge candidate 222, the method 400 defines a height of the respective stair 20 based on sensor data height about the detected edge 212. At operation 406, the method 400 generates a staircase model 202 including stairs 20 with respective edges 26 at the respective defined heights.

[0102] FIG. 5 is a flow chart of an example arrangement of operations for a method of controlling a robot based on fused modeled and perceived terrain. At operation 502, the method 500 receives sensor data 134 about an environment 10 of the robot 100. At operation 504, the method 500 generates a set of maps 182 based on voxels corresponding to the received sensor data 134. The set of maps 182 including a ground height map 182a and a map of movement limitations 182 for the robot 100. The map of movement limitations 182 identifying illegal regions within the environment 10 that the robot 100 should avoid entering. At operation 506, the method 500 generates a stair model 202 for a set of stairs 20 within the environment 10 based on the sensor data 134. At operation 508, the method 500 merges the stair model 202 and the map of the movement limitations 182 to generate an enhanced stair map. At operation 510, the method 500 controls the robot 100 based on the enhanced stair map or the ground height map 182a to traverse the environment 10.

[0103] FIG. 6 is schematic view of an example computing device 600 that may be used to implement the systems (e.g., the control system 170, the perception system 180, the stair tracker 200, and the stair supervisor 300) and methods (e.g., the method 400, 500) described in this document. The computing device 600 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.

[0104] The computing device 600 includes a processor 610 (e.g., data processing hardware), memory 620 (e.g.,

memory hardware), a storage device 630, a high-speed interface/controller 640 connecting to the memory 620 and high-speed expansion ports 650, and a low speed interface/controller 660 connecting to a low speed bus 670 and a storage device 630. Each of the components 610, 620, 630, 640, 650, and 660, are interconnected using various busses, and may be mounted on a common motherboard or in other manners as appropriate. The processor 610 can process instructions for execution within the computing device 600, including instructions stored in the memory 620 or on the storage device 630 to display graphical information for a graphical user interface (GUI) on an external input/output device, such as display 680 coupled to high speed interface 640. 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 600 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).

[0105] The memory 620 stores information non-transitorily within the computing device 600. The memory 620 may be a computer-readable medium, a volatile memory unit(s), or non-volatile memory unit(s). The non-transitory memory 620 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 600. 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.

[0106] The storage device 630 is capable of providing mass storage for the computing device 600. In some implementations, the storage device 630 is a computer-readable medium. In various different implementations, the storage device 630 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 620, the storage device 630, or memory on processor 610.

[0107] The high speed controller 640 manages bandwidth-intensive operations for the computing device 600, while the low speed controller 660 manages lower bandwidth-intensive operations. Such allocation of duties is exemplary only. In some implementations, the high-speed controller 640 is coupled to the memory 620, the display 680 (e.g., through a graphics processor or accelerator), and to the high-speed expansion ports 650, which may accept various expansion cards (not shown). In some implementations, the low-speed controller 660 is coupled to the storage device 630 and a low-speed expansion port 690. The low-speed expansion

port **690**, 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.

[0108] The computing device **600** may be implemented in a number of different forms, as shown in the figure. For example, it may be implemented as a standard server **600a** or multiple times in a group of such servers **600a**, as a laptop computer **600b**, as part of a rack server system **600c**, or as the robot **100**.

[0109] 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.

[0110] 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.

[0111] 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.

[0112] 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.

[0113] 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 robot causes the data processing hardware to perform operations comprising:

determining that the robot is proximate a descending set of stairs, the robot comprising a front body portion having at least one front leg and a rear body portion having at least one hind leg, the at least one hind leg comprising:

an upper member;

a hip joint coupling the upper member to the rear body portion;

a lower member; and

a knee joint coupling the lower member to the upper member;

instructing the robot to assume an initial stair descent pose by:

orienting the rear body portion to face the descending set of stairs; and

placing the at least one of the hind leg in a stance phase, the stance phase defined by the knee joint extending further outward from the rear body portion toward the descending set of stairs than the hip joint; and

instructing the robot to descend the descending set of stairs starting from the initial stair descent pose.

2. The method of claim 1, wherein the robot includes more vision sensors on the front body portion than on the rear body portion.

3. The method of claim 2, wherein:

the vision sensors of the robot comprise stereo cameras; and

the robot includes two stereo cameras at the front body portion and one stereo camera at the rear body portion.

4. The method of claim 1, wherein determining that the robot is proximate the descending set of stairs comprises

determining that a support surface for the robot terminates at a floor edge adjacent a current location of the robot.

5. The method of claim **4**, wherein determining that the support surface for the robot terminates at the floor edge comprises:

determining that sensor data captured by the robot indicates that the support surface disappears in a straight line; and

identifying the location of the straight line as a top stair edge for a top stair of the descending set of stairs.

6. The method of claim **1**, wherein the operations further comprise:

receiving sensor data captured by one or more sensors associated with the robot; and

classifying the sensor data by height with respect to a gravitational axis of the robot, the sensor data classified as a floor classification corresponding to a height of a support surface for the robot and a below-floor classification corresponding to a height below the support surface in a direction away from the robot,

wherein determining that the robot is proximate the descending set of stairs comprises detecting that the robot is proximate the descending set of stairs by determining that the sensor data at a location adjacent the robot transitions from the floor classification to the below-floor classification.

7. The method of claim **6**, wherein the operations further comprise translating the sensor data from a three dimensional image space to a two dimensional image space, at least one dimension of the two dimensional image space corresponding to a height coordinate that indicates a height value for a volumetric point from the sensor data with respect to the gravitation axis of the robot.

8. The method of claim **6**, wherein the one or more sensors are disposed on the rear body portion of the robot and have a field of view extending away from the front body portion and toward the descending set of stairs.

9. The method of claim **1**, wherein the operations further comprise, based on determining that the robot is proximate the descending set of stairs, activating a stair mode to coordinate with one or more controllers dedicated to stair traversal.

10. The method of claim **1**, wherein the operations further comprise, while the robot is descending the descending set of stairs:

receiving sensor data captured by one or more sensors associated with the robot;

classifying the sensor data by height with respect to a gravitational axis of the robot, the sensor data classified as a stair tread classification corresponding to a height of a stair tread supporting the robot and a below-tread classification corresponding to a height below the stair tread support surface in a direction away from the robot; and

determining a foot placement location for the robot based on a cluster of below-tread classifications.

11. A robot comprising:

a front body portion having at least one front leg;
a rear body portion having at least one hind leg, the at least one hind leg comprising:
an upper member;
a hip joint coupling the upper member to the rear body portion;

a lower member; and
a knee joint coupling the lower member to the upper member; and

a stair traversal system configured to coordinate stair traversal for the robot, the stair traversal system comprising data processing hardware and memory hardware, the memory hardware including instructions that when executed by the data processing hardware perform operations comprising:

determining that the robot is proximate a descending set of stairs;

instructing the robot to assume an initial stair descent pose by:

orienting the rear body portion to face the descending set of stairs; and

placing the at least one of the hind leg in a stance phase, the stance phase defined by the knee joint extending further outward from the rear body portion toward the descending set of stairs than the hip joint; and

instructing the robot to descend the descending set of stairs starting from the initial stair descent pose.

12. The robot of claim **11**, wherein the robot includes more vision sensors on the front body portion than on the rear body portion.

13. The robot of claim **12**, wherein:
the vision sensors of the robot comprise stereo cameras; and

the robot includes two stereo cameras at the front body portion and one stereo camera at the rear body portion.

14. The robot of claim **11**, wherein determining that the robot is proximate the descending set of stairs comprises determining that a support surface for the robot terminates at a floor edge adjacent a current location of the robot.

15. The robot of claim **14**, wherein determining that the support surface for the robot terminates at the floor edge comprises:

determining that sensor data captured by the robot indicates that the support surface disappears in a straight line; and

identifying the location of the straight line as a top stair edge for a top stair of the descending set of stairs.

16. The robot of claim **11**, wherein the operations further comprise:

receiving sensor data captured by one or more sensors associated with the robot; and

classifying the sensor data by height with respect to a gravitational axis of the robot, the sensor data classified as a floor classification corresponding to a height of a support surface for the robot and a below-floor classification corresponding to a height below the support surface in a direction away from the robot,

wherein determining that the robot is proximate the descending set of stairs comprises detecting that the robot is proximate the descending set of stairs by determining that the sensor data at a location adjacent the robot transitions from the floor classification to the below-floor classification.

17. The robot of claim **16**, wherein the operations further comprise translating the sensor data from a three dimensional image space to a two dimensional image space, at least one dimension of the two dimensional image space corresponding to a height coordinate that indicates a height

value for a volumetric point from the sensor data with respect to the gravitation axis of the robot.

18. The robot of claim **16**, wherein the one or more sensors are disposed on the rear body portion of the robot and have a field of view extending away from the front body portion and toward the descending set of stairs.

19. The robot of claim **11**, wherein the operations further comprise, based on determining that the robot is proximate the descending set of stairs, activating a stair mode to coordinate with one or more controllers dedicated to stair traversal.

20. The robot of claim **11**, wherein the operations further comprise, while the robot is descending the descending set of stairs:

- receiving sensor data captured by one or more sensors associated with the robot;

- classifying the sensor data by height with respect to a gravitational axis of the robot, the sensor data classified as a stair tread classification corresponding to a height of a stair tread supporting the robot and a below-tread classification corresponding to a height below the stair tread support surface in a direction away from the robot; and

- determining a foot placement location for the robot based on a cluster of below-tread classifications.

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