US 20160188977A1

(19) United States
(12) Patent Application Publication
(10) Pub. No.: US 2016/0188977 A1
(43) Pub. Date: Jun. 30, 2016
Kearns et al.

(54) **MOBILE SECURITY ROBOT**

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(21) Appl. No.: **14/944,354**

(22) Filed: **Nov. 18, 2015**

**Related U.S. Application Data**

(60) Provisional application No. 62/096,747, filed on Dec. 24, 2014.

**Publication Classification**

(51) **Int. Cl.**

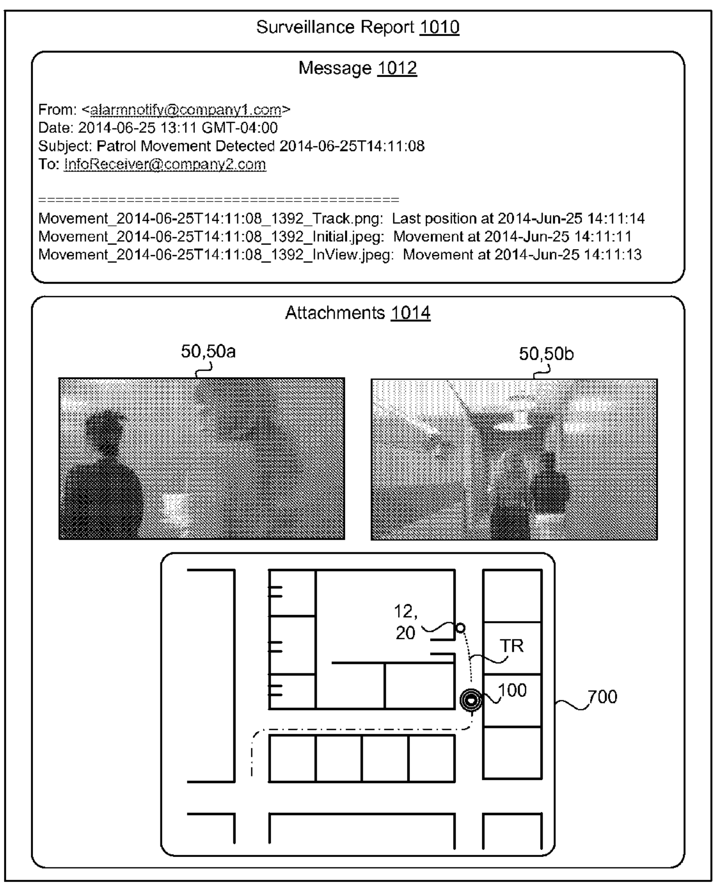
| | |
|---|---|
| ***G06K 9/00*** | (2006.01) |
| ***G06T 7/00*** | (2006.01) |
| ***B25J 11/00*** | (2006.01) |
| ***G06T 7/60*** | (2006.01) |
| ***G06T 7/20*** | (2006.01) |
| ***G06F 17/30*** | (2006.01) |
| ***H04N 7/18*** | (2006.01) |
| ***G06K 9/52*** | (2006.01) |

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

CPC .............. ***G06K 9/00664*** (2013.01); ***H04N 7/18*** (2013.01); ***G06K 9/00288*** (2013.01); ***G06T 7/0079*** (2013.01); ***G06K 9/52*** (2013.01); ***G06T 7/60*** (2013.01); ***G06T 7/2033*** (2013.01); ***G06F 17/30268*** (2013.01); ***G06K 9/00476*** (2013.01); ***B25J 11/002*** (2013.01); *G06T 2207/30201* (2013.01); *G06T 2207/20112* (2013.01); *G06T 2207/20024* (2013.01)

(57) **ABSTRACT**

A method of operating a mobile robot includes receiving a layout map corresponding to a patrolling environment at a computing device and maneuvering the robot in the patrolling environment based on the received layout map. The method further includes receiving imaging data of a scene about the robot when the robot maneuvers in the patrolling environment at the computing device. The imaging data is received from one or more imaging sensors disposed on the robot and in communication with the computing device. The method further includes identifying a person in the scene based on the received imaging data and aiming a field of view of at least one imaging sensor to continuously perceive the identified person in the field of view. The method further includes capturing a human recognizable image of the identified person using the at least one imaging sensor.



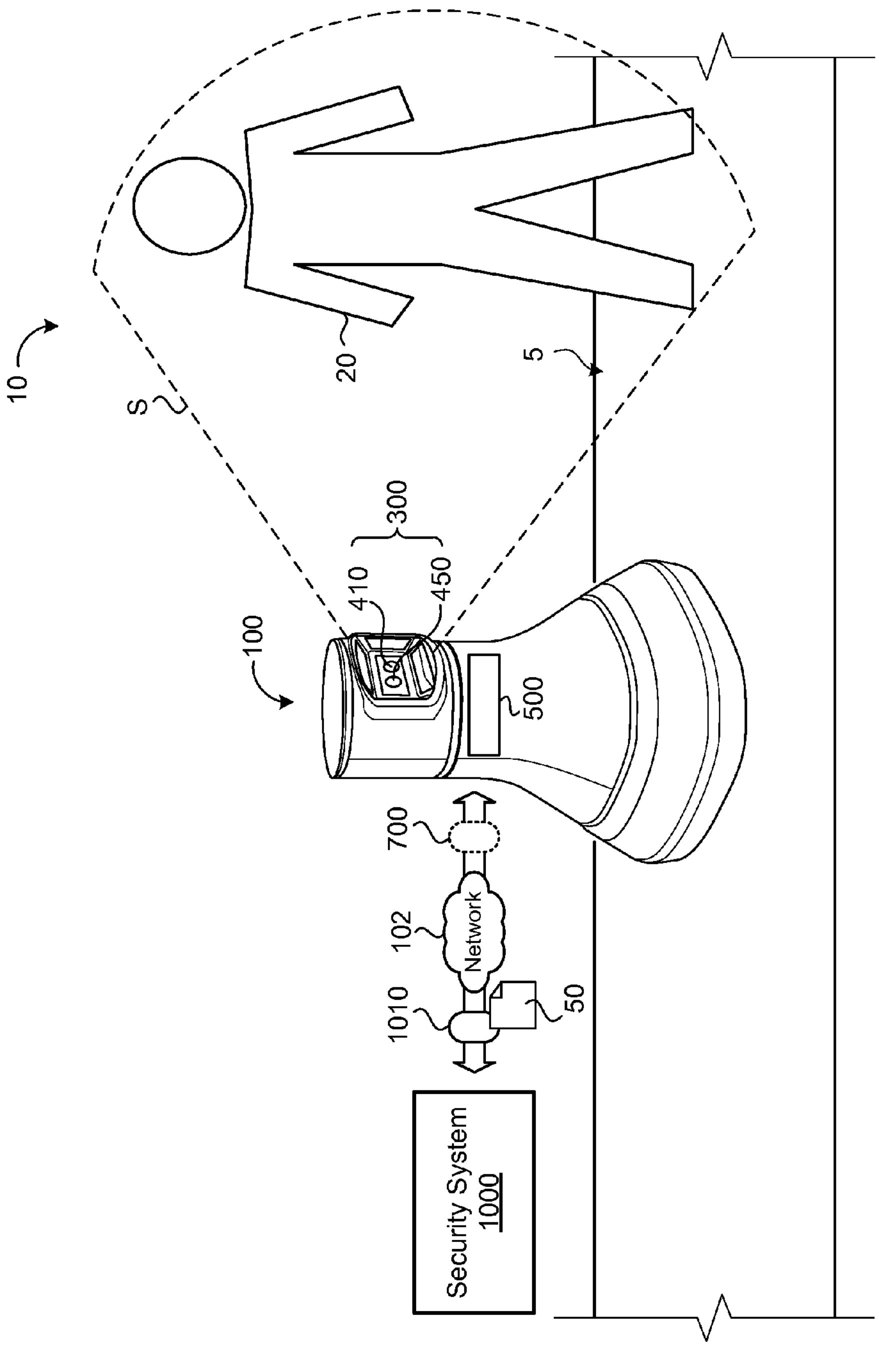

10
S
20
5
300
410
450
100
500
700
102
Network
1010
50
Security System
1000

FIG. 1A

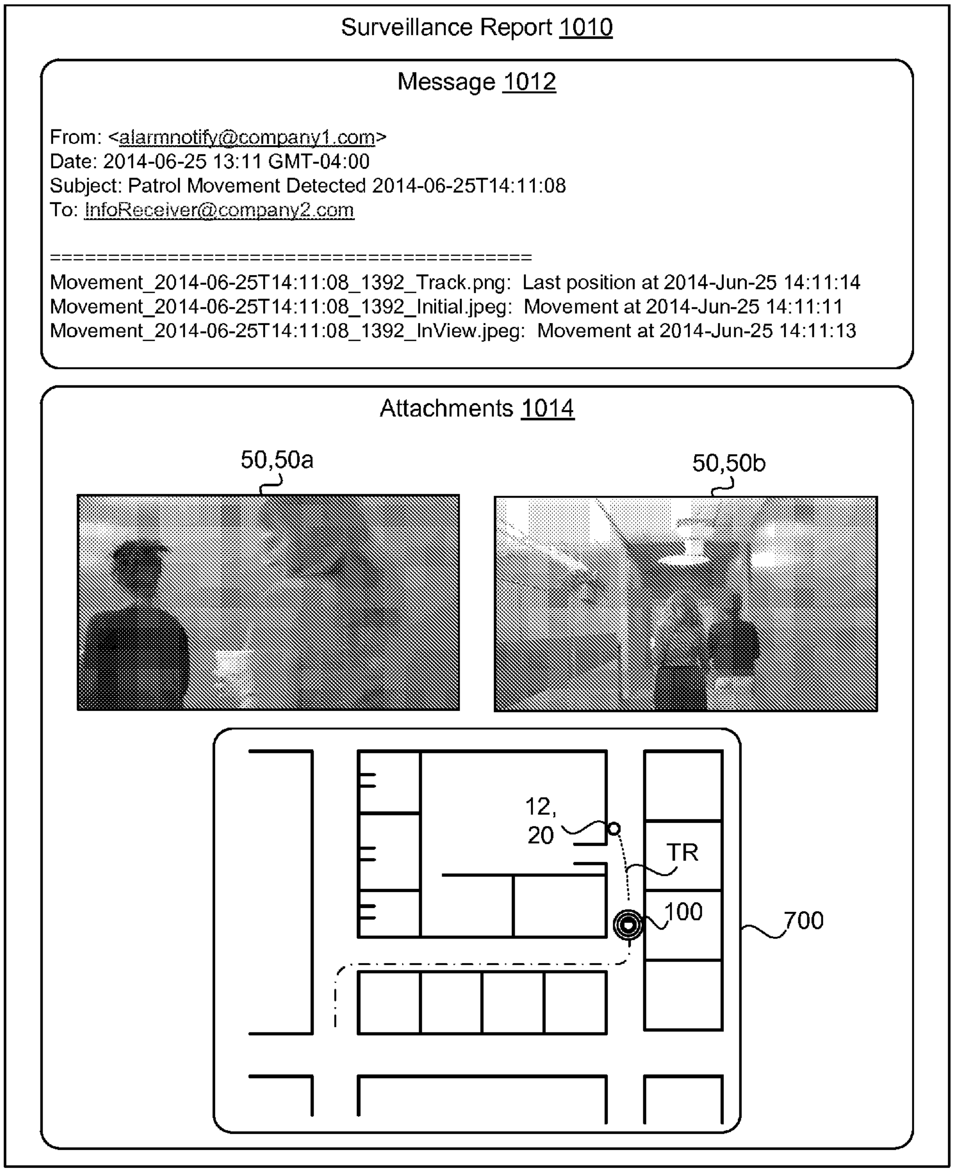

Surveillance Report 1010
Message 1012
From: <alarmnotify@company1.com>
Date: 2014-06-25 13:11 GMT-04:00
Subject: Patrol Movement Detected 2014-06-25T14:11:08
To: InfoReceiver@company2.com
========================================
Movement_2014-06-25T14:11:08_1392_Track.png: Last position at 2014-Jun-25 14:11:14
Movement_2014-06-25T14:11:08_1392_Initial.jpeg: Movement at 2014-Jun-25 14:11:11
Movement_2014-06-25T14:11:08_1392_InView.jpeg: Movement at 2014-Jun-25 14:11:13
Attachments 1014
50,50a
50,50b
12,
20
TR
100
700

FIG. 1B

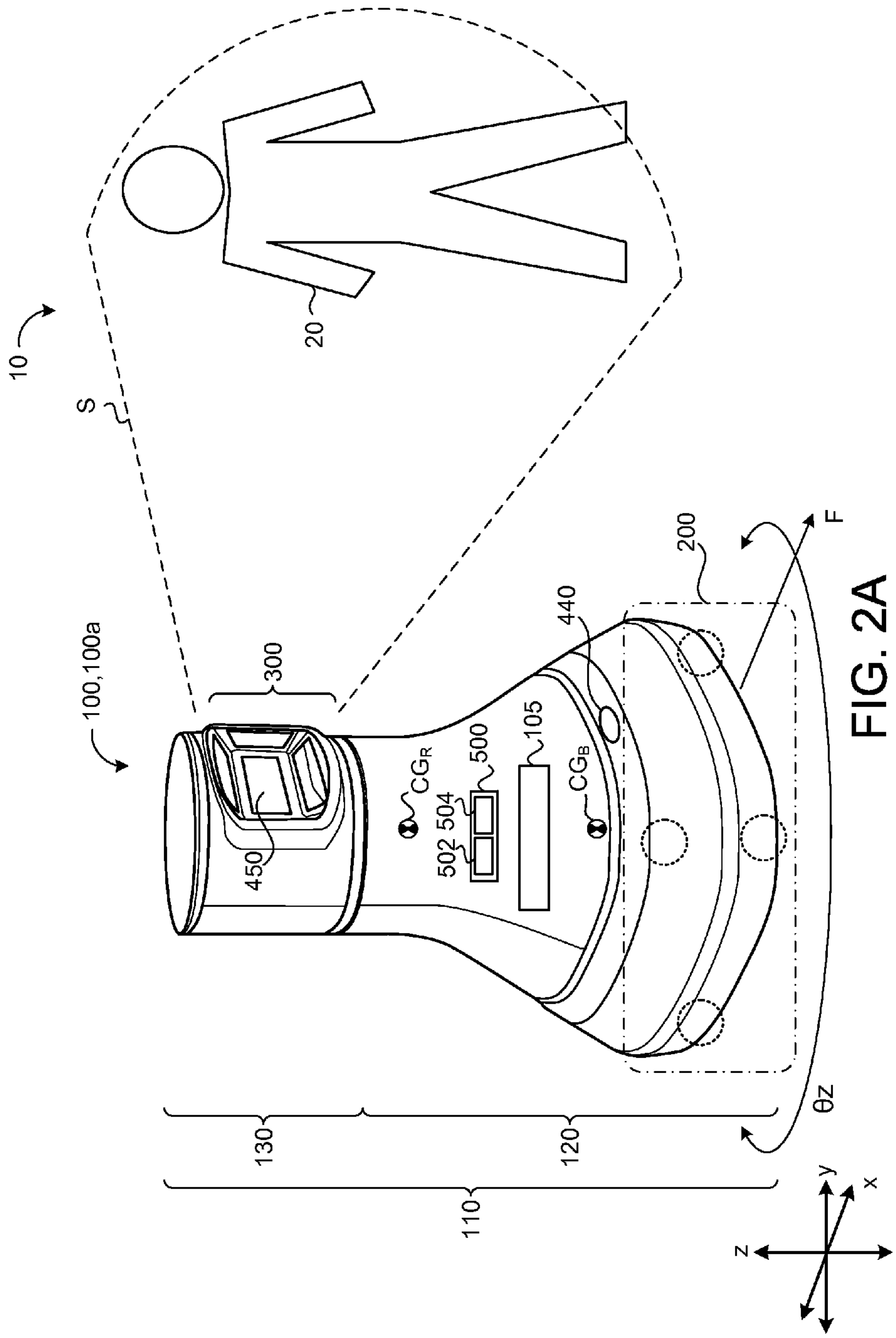

10
S
20
100,100a
300
440
200
F
105
500
502 504
$CG_R$
$CG_B$
450
130
120
110
θz
x
y
z

FIG. 2A

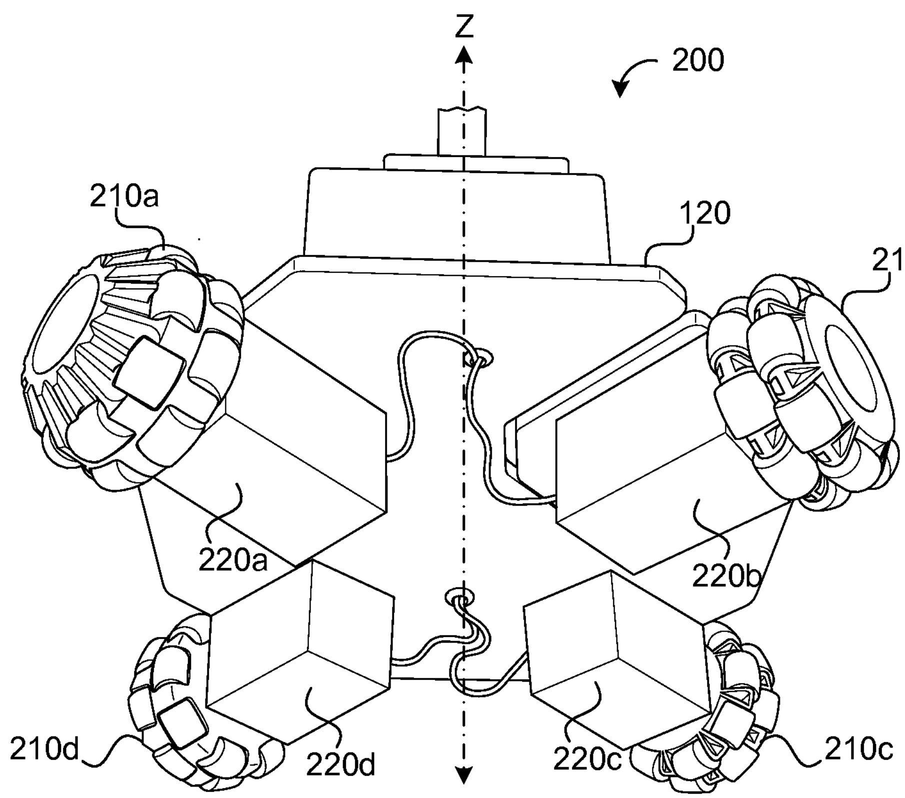



FIG. 2B

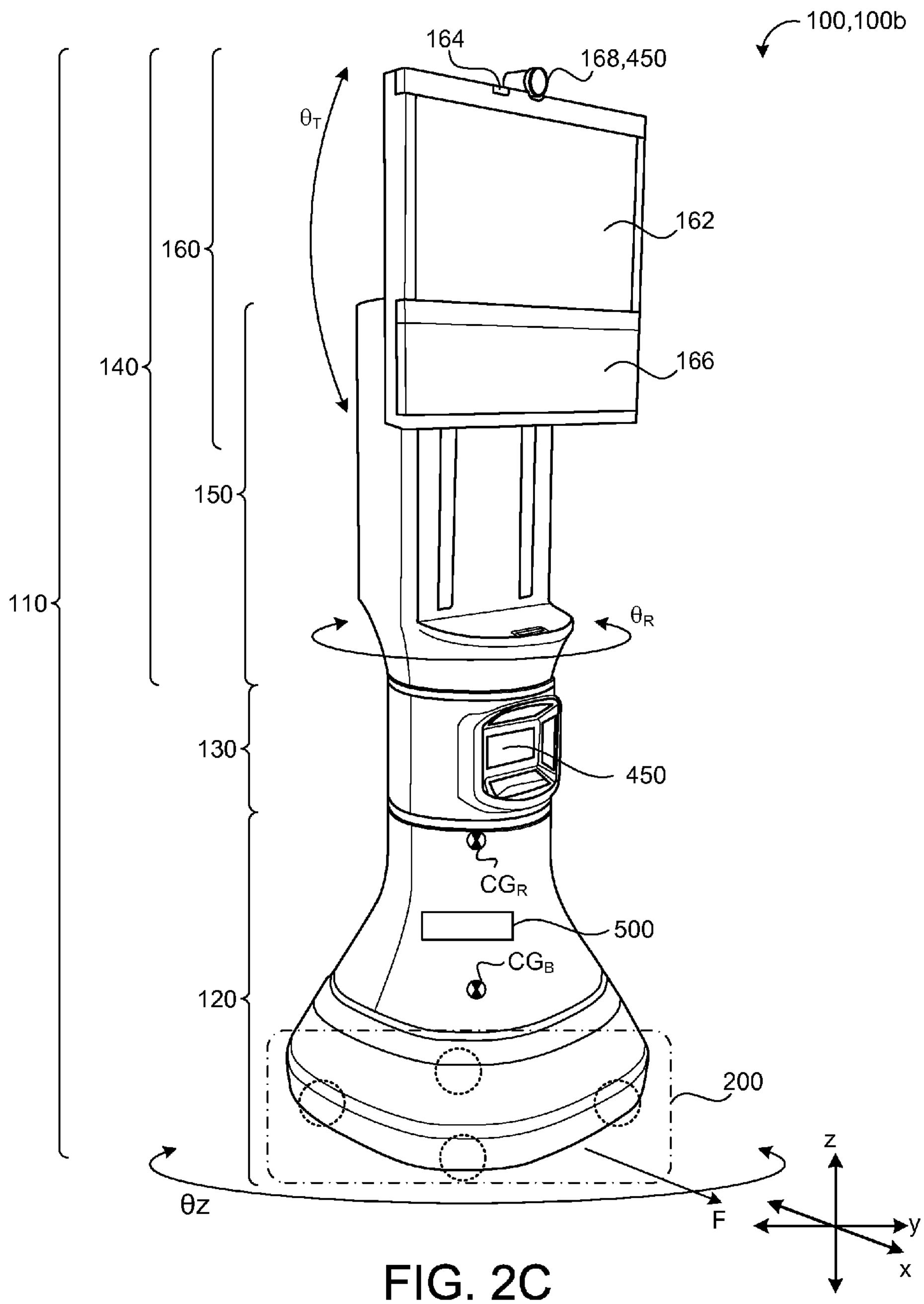

100,100b
164
168,450
θT
162
160
140
166
150
110
θR
130
450
CGR
500
CGB
120
200
z
y
x
θz
F

FIG. 2C

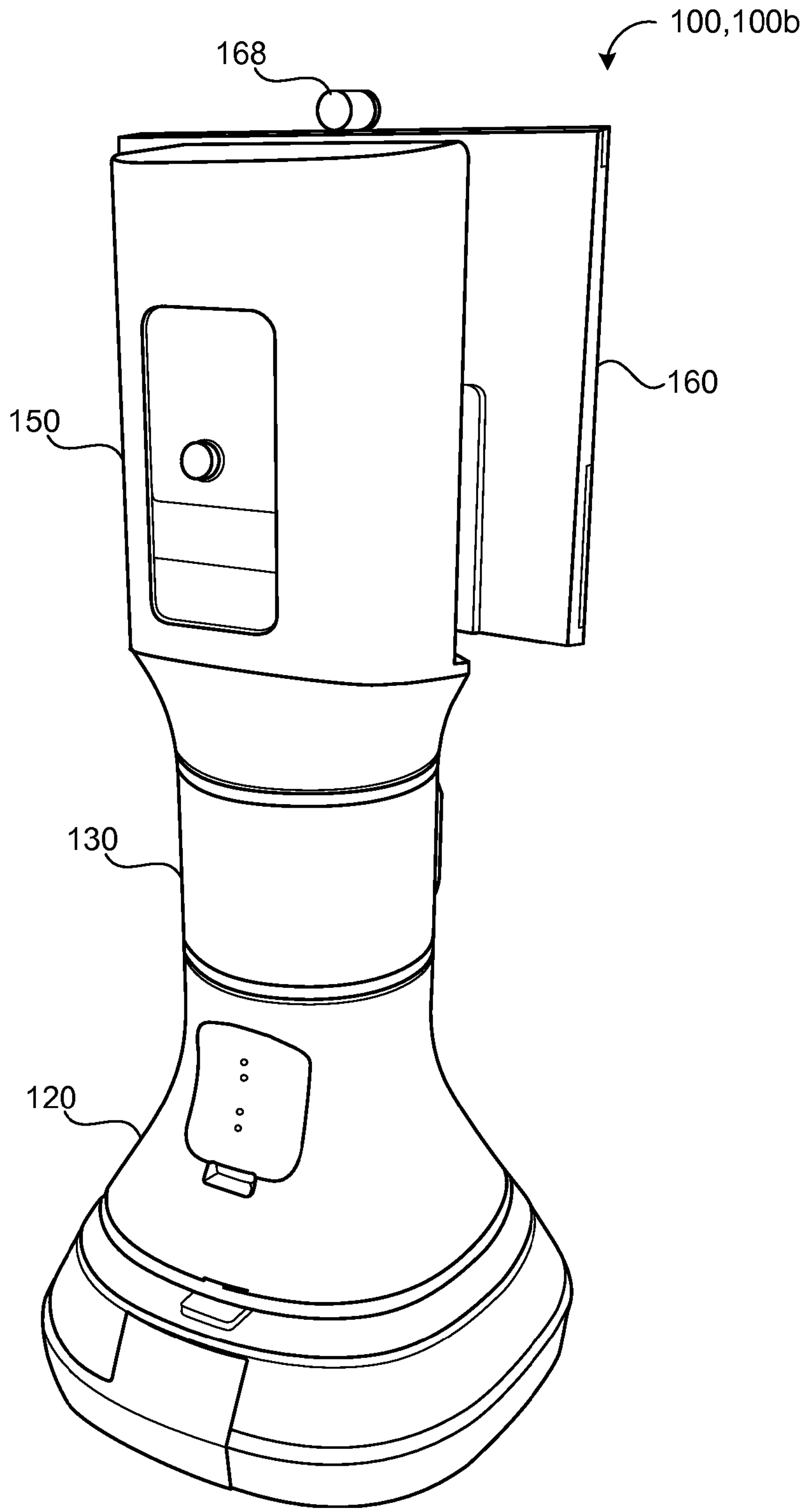



FIG. 2D

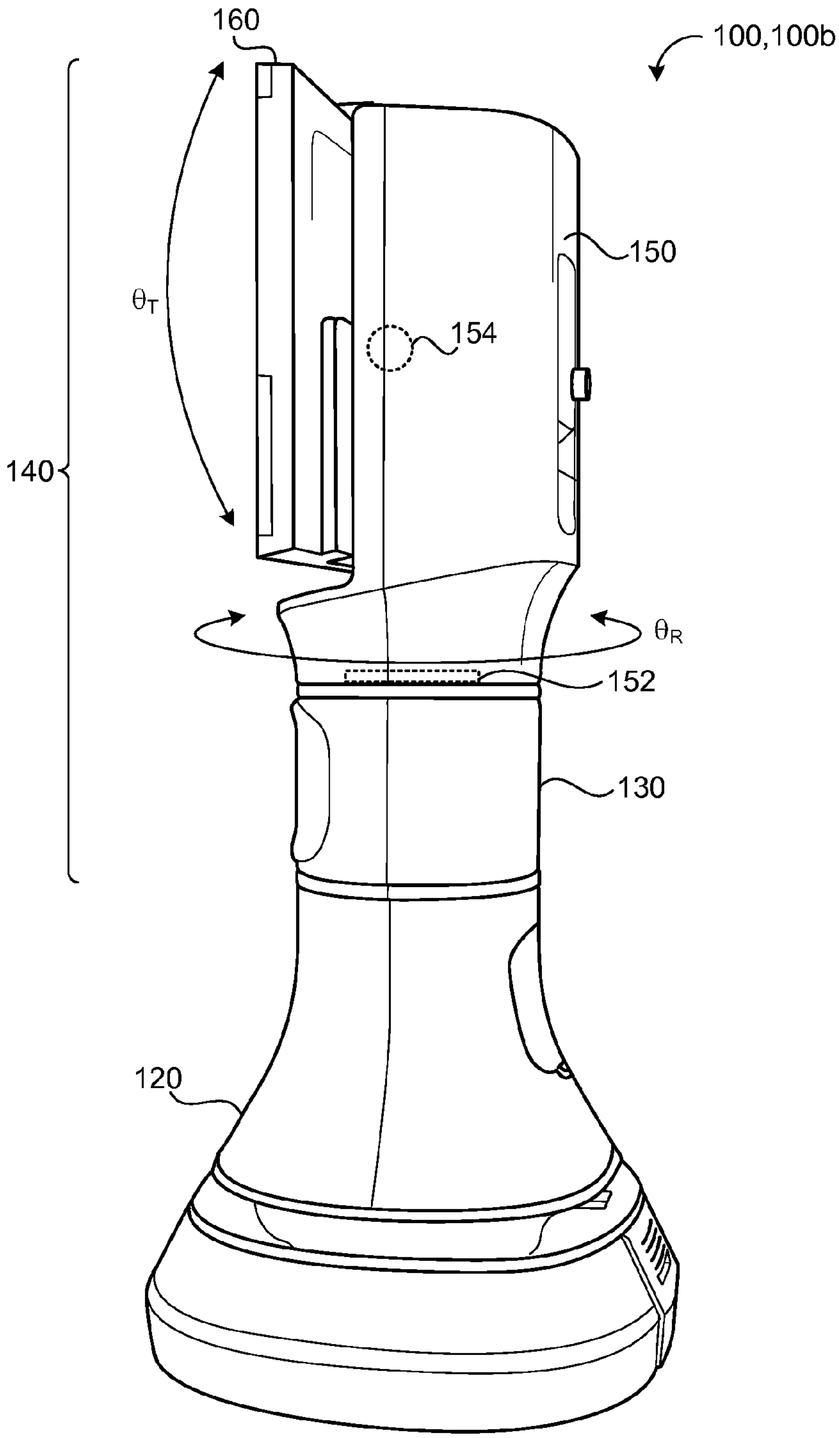



FIG. 2E

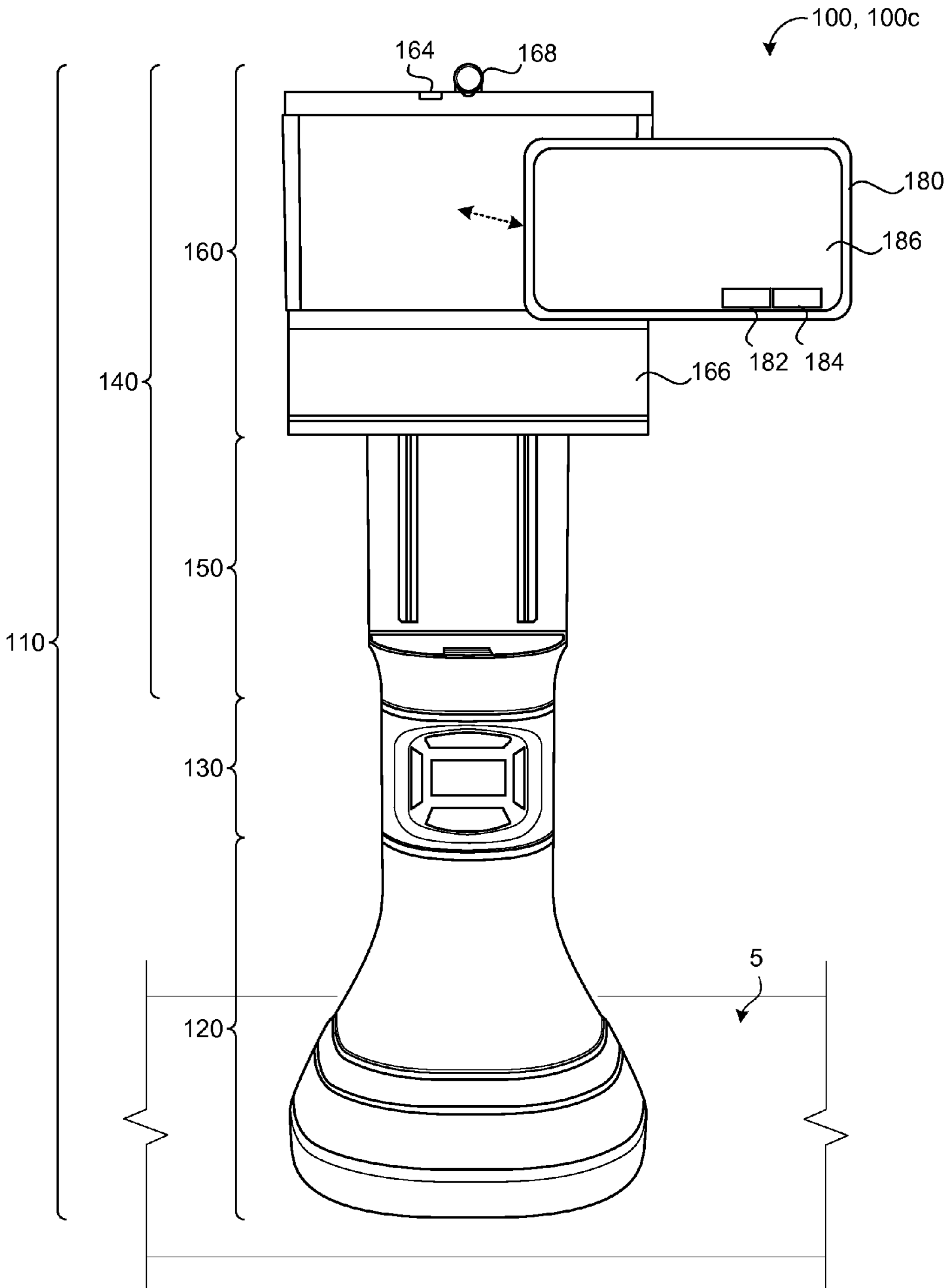



FIG. 2F

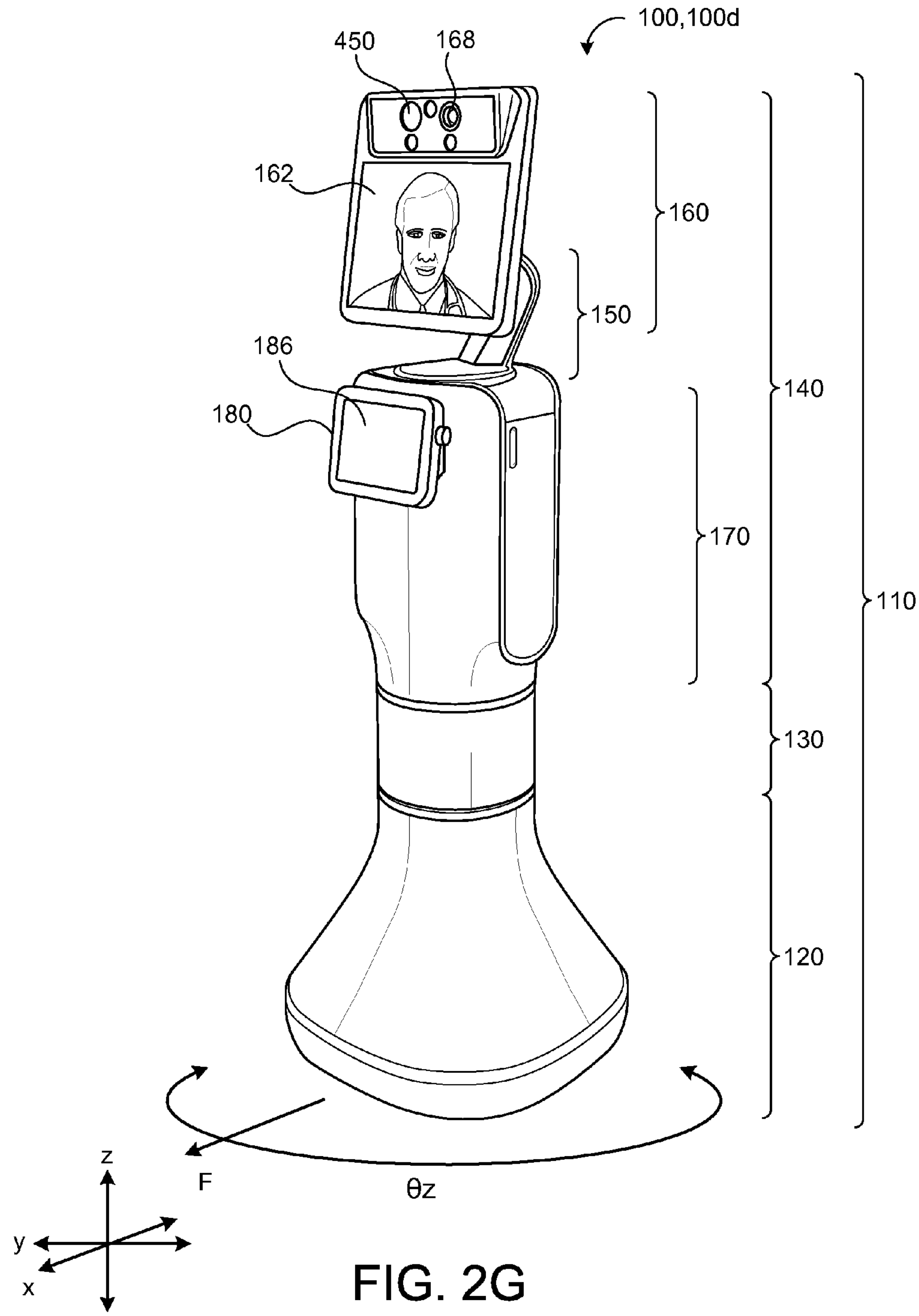



FIG. 2G

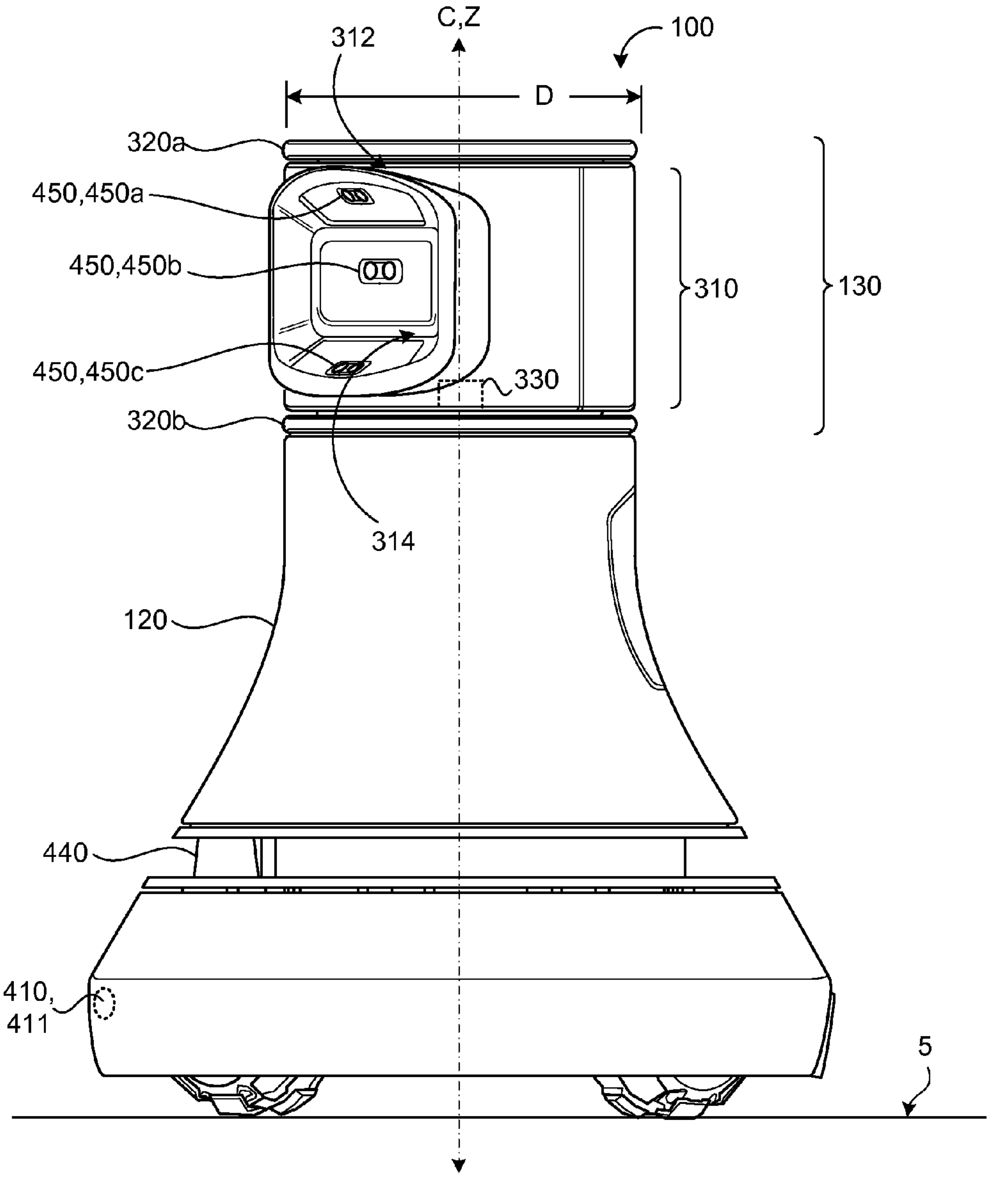
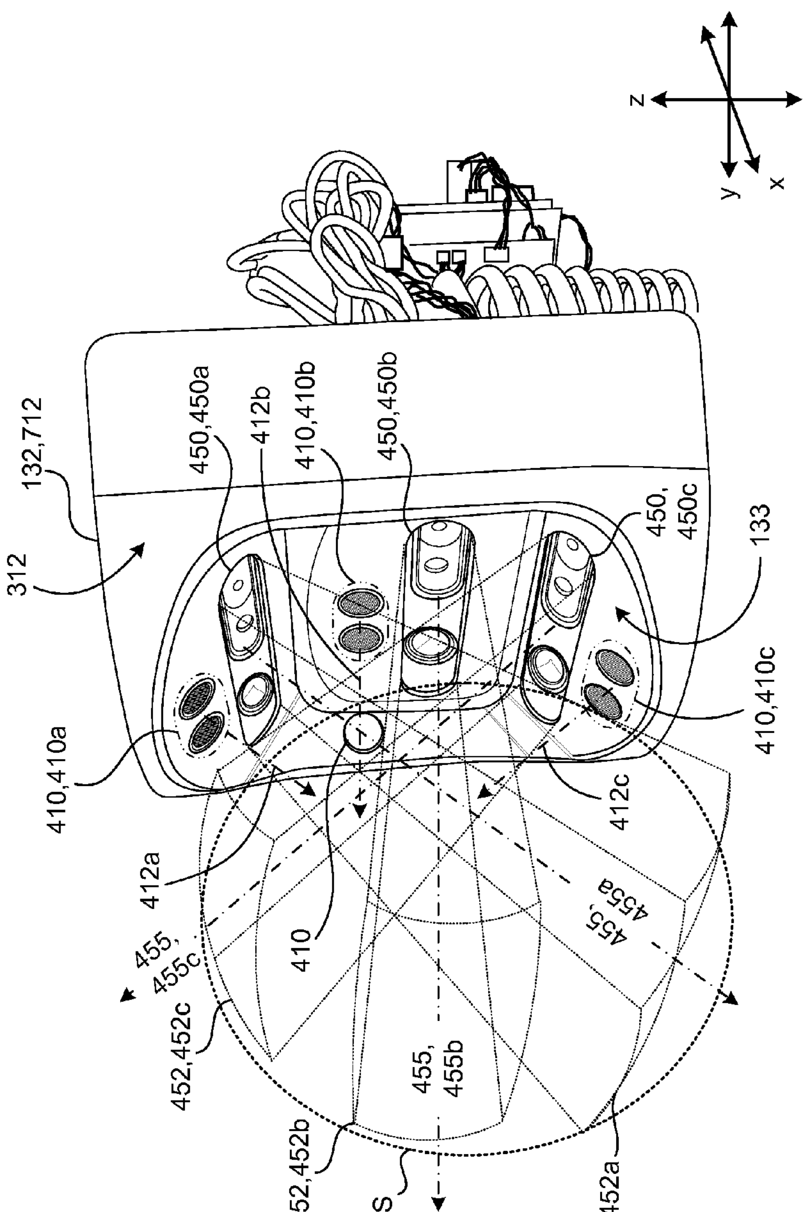

C,Z
100
312
D
320a
450,450a
450,450b
310
130
450,450c
330
320b
314
120
440
410,
411
5

FIG. 3A



140,700
132,712
312
450,450a
412b
410,410b
450,450b
450,
450c
133
410,410a
410,410c
412c
412a
410
455,
455a
455,
455c
455,
455b
452,452c
452,452b
S
452,452a
z
y
x


FIG. 3B

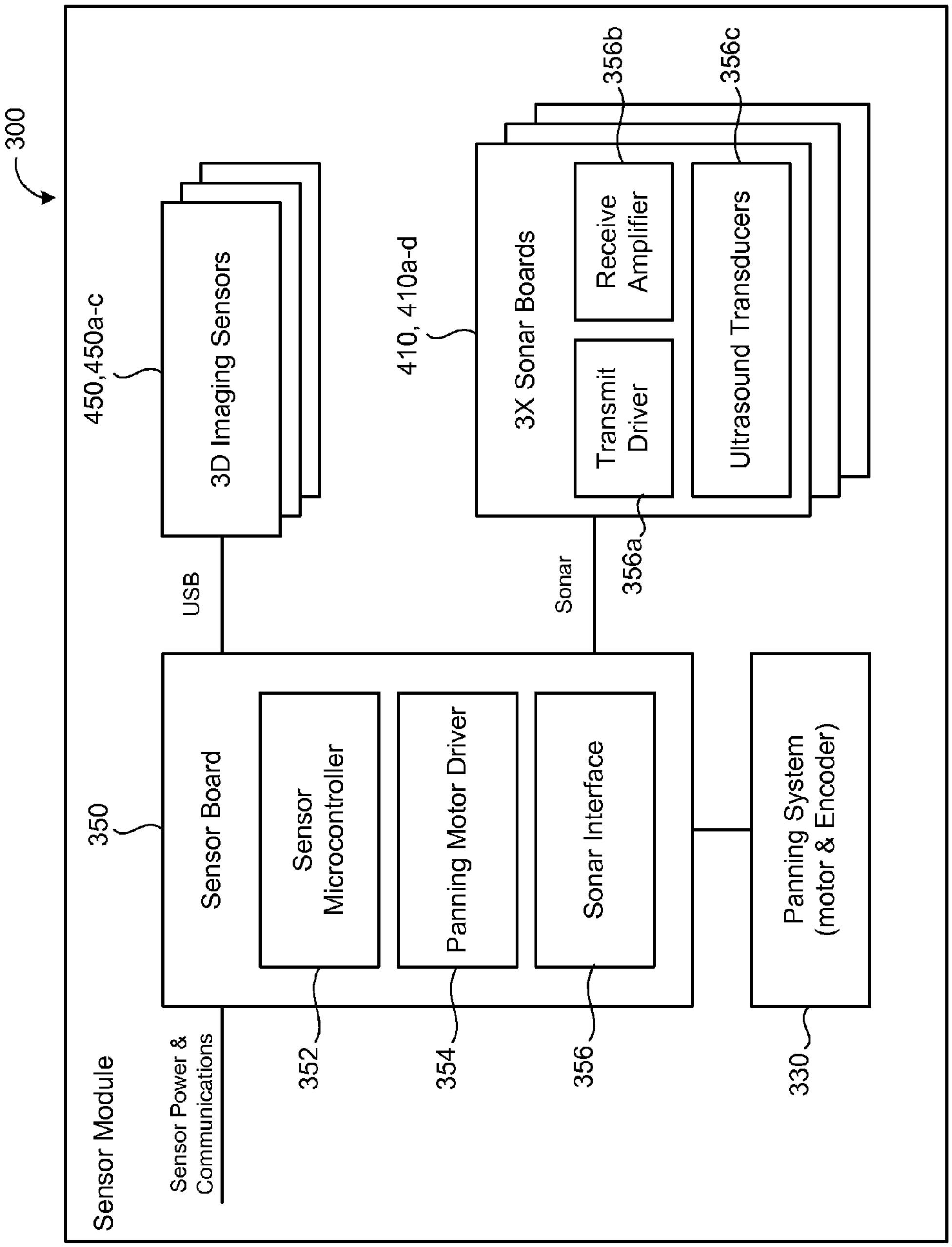

300
Sensor Module
Sensor Power &
Communications
350
Sensor Board
Sensor
Microcontroller
Panning Motor Driver
Sonar Interface
352
354
356
Panning System
(motor & Encoder)
330
USB
450,450a-c
3D Imaging Sensors
Sonar
410, 410a-d
3X Sonar Boards
Transmit
Driver
Receive
Amplifier
Ultrasound Transducers
356a
356b
356c

FIG. 3C

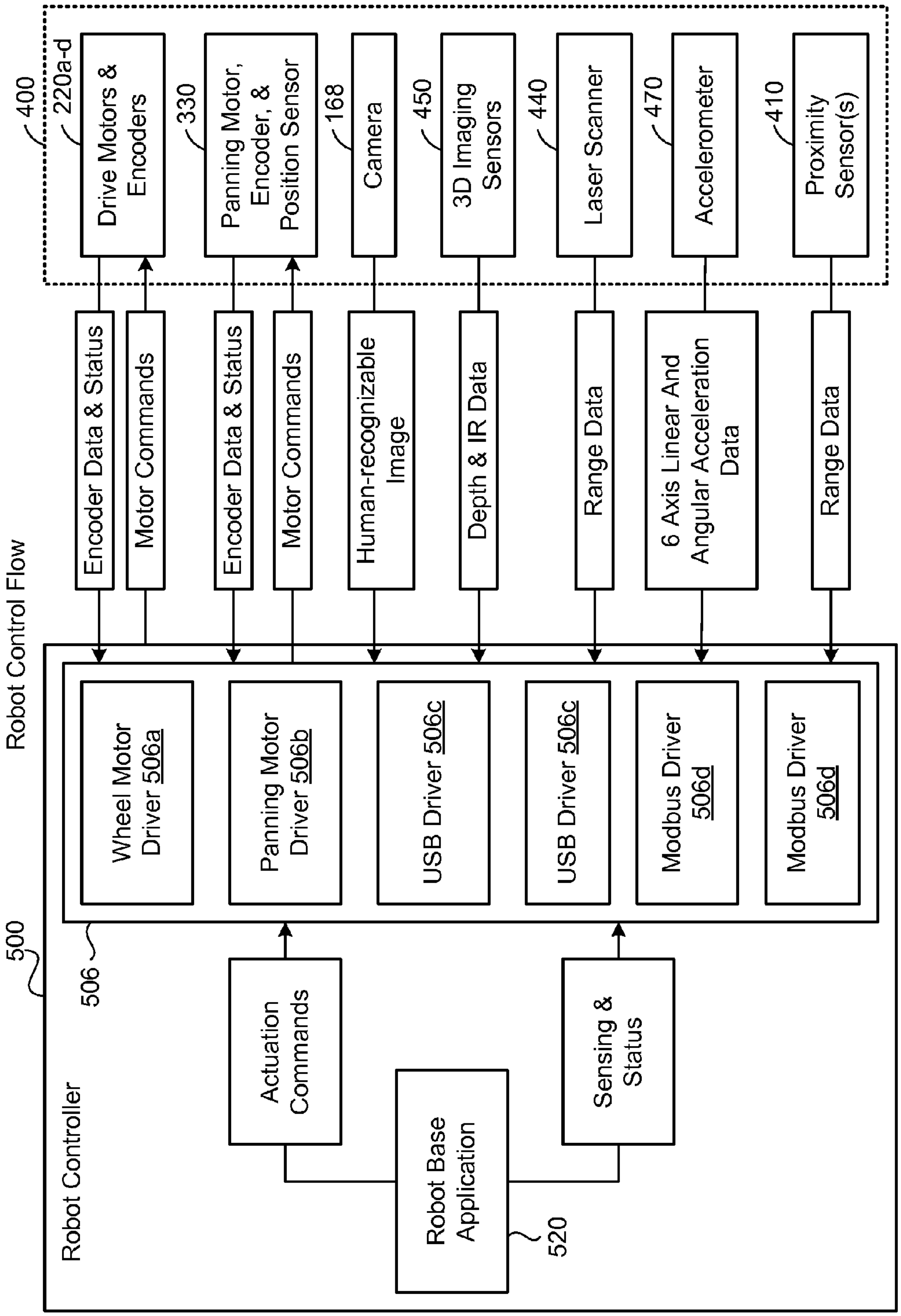

Robot Control Flow
400
220a-d
Drive Motors & Encoders
330
Panning Motor, Encoder, & Position Sensor
168
Camera
450
3D Imaging Sensors
440
Laser Scanner
470
Accelerometer
410
Proximity Sensor(s)
Encoder Data & Status
Motor Commands
Encoder Data & Status
Motor Commands
Human-recognizable Image
Depth & IR Data
Range Data
6 Axis Linear And Angular Acceleration Data
Range Data
500
506
Wheel Motor Driver 506a
Panning Motor Driver 506b
USB Driver 506c
USB Driver 506c
Modbus Driver 506d
Modbus Driver 506d
Actuation Commands
Sensing & Status
Robot Base Application
520
Robot Controller

FIG. 4

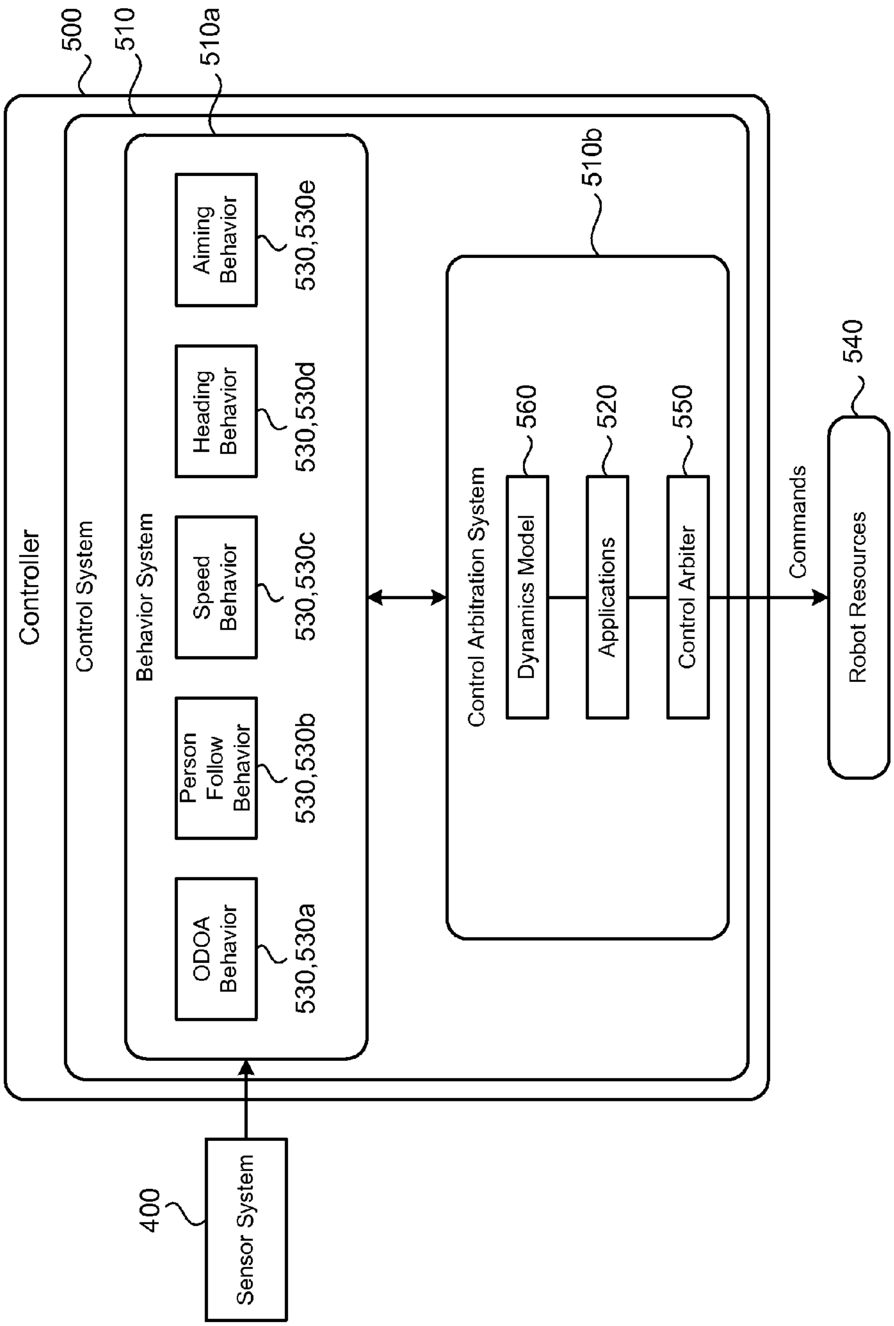

500
510
510a
Controller
Control System
Behavior System
ODOA Behavior
530,530a
Person Follow Behavior
530,530b
Speed Behavior
530,530c
Heading Behavior
530,530d
Aiming Behavior
530,530e
510b
Control Arbitration System
Dynamics Model
560
Applications
520
Control Arbiter
550
Commands
Robot Resources
540
Sensor System
400

FIG. 5

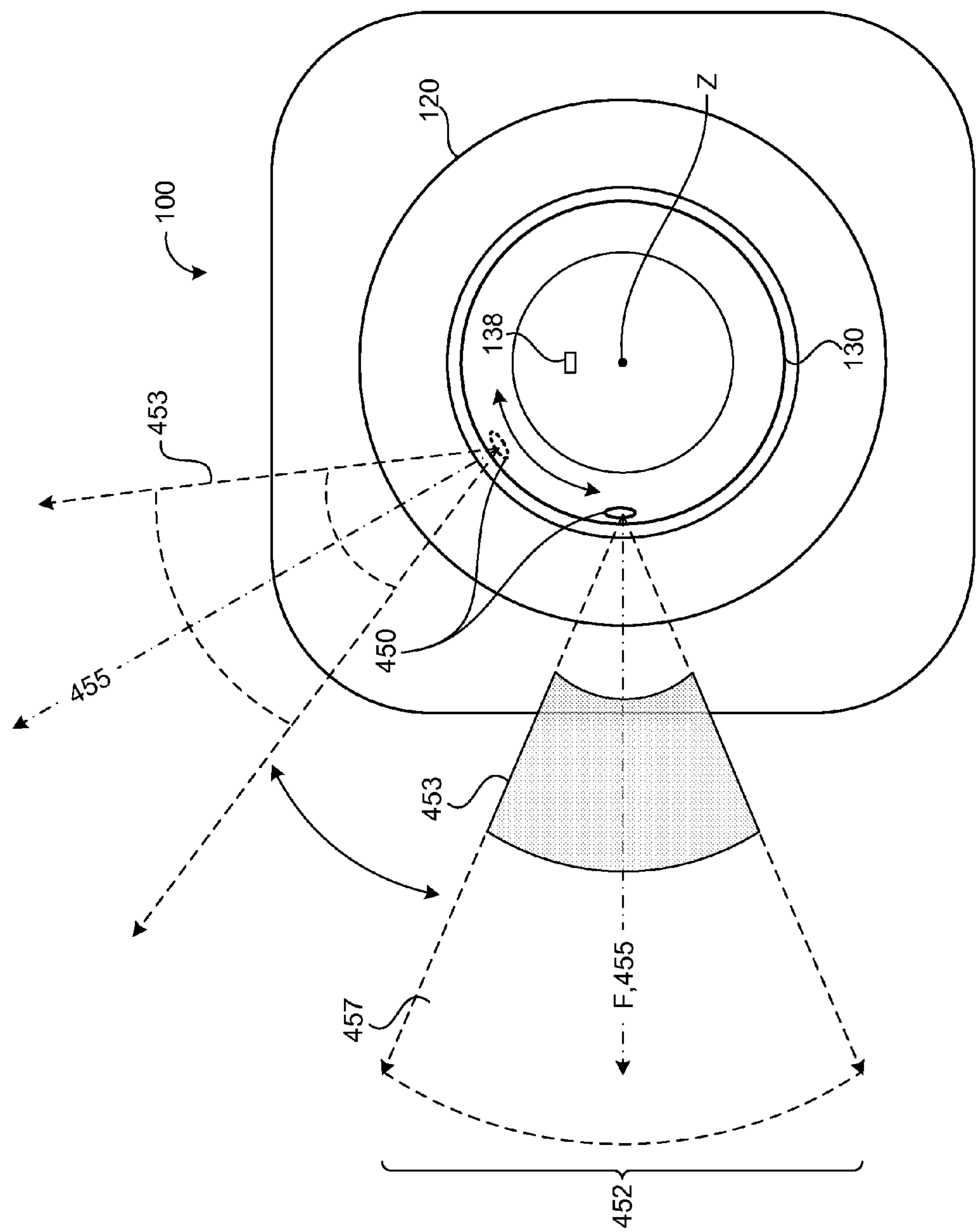



FIG. 6A

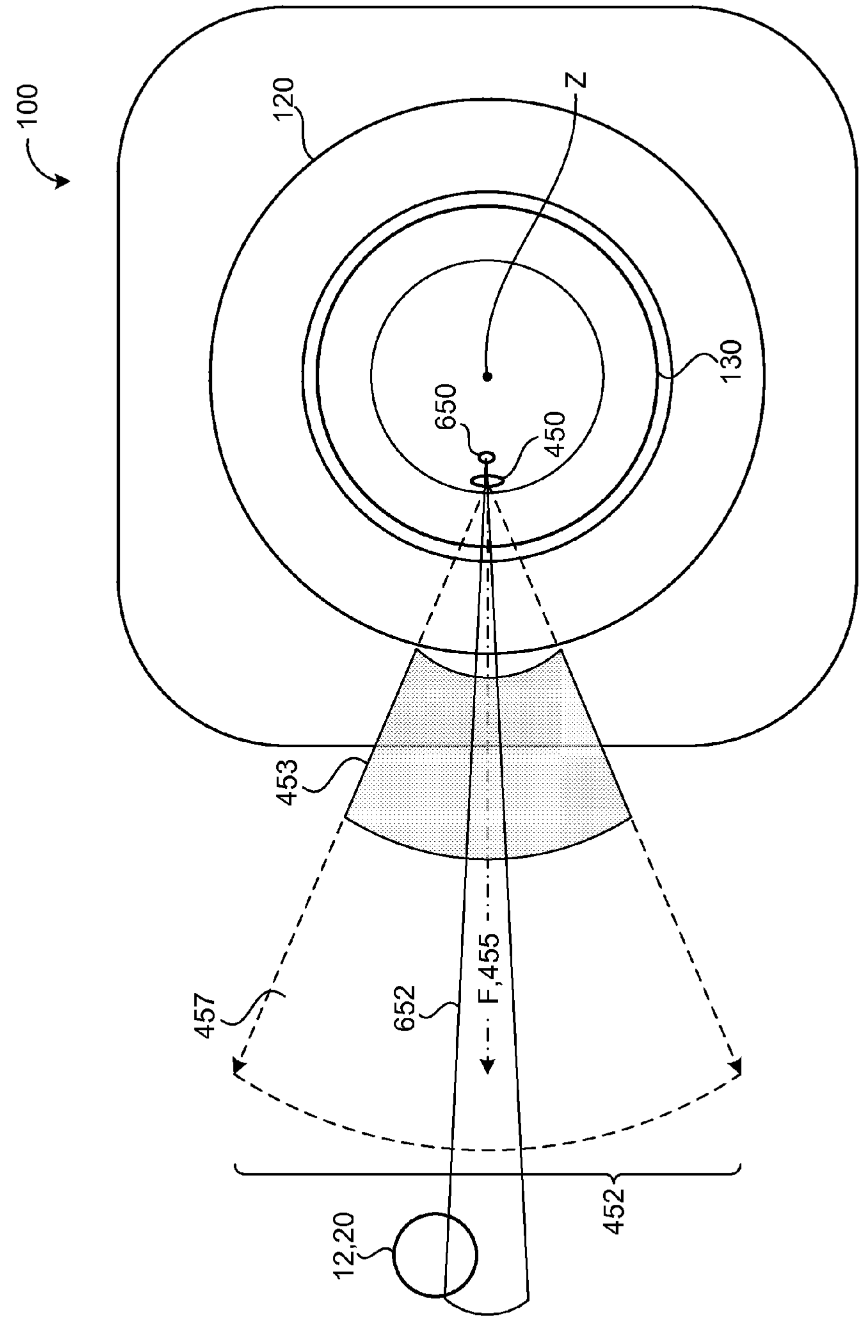



FIG. 6B

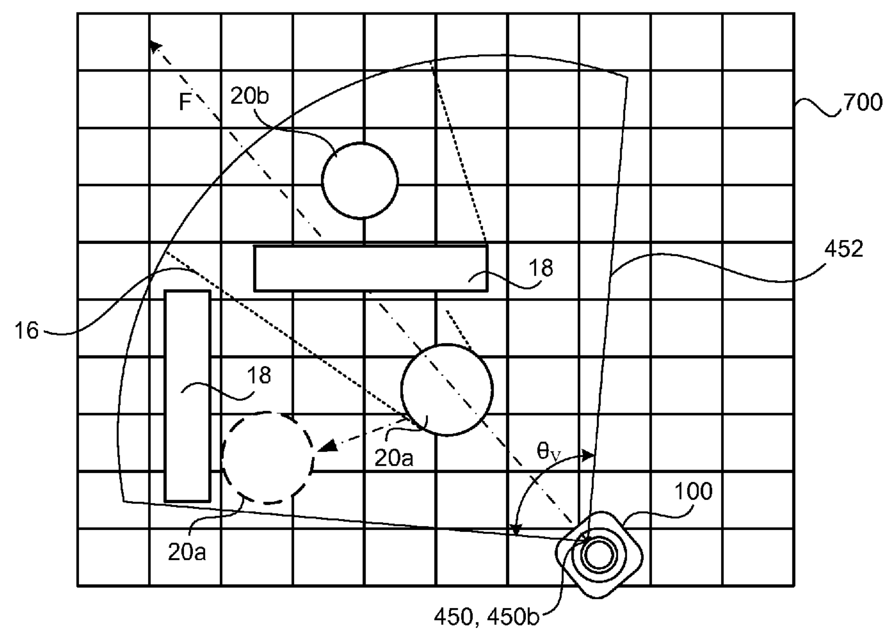

F
20b
700
452
18
16
18
20a
θV
100
20a
450, 450b

FIG. 7A

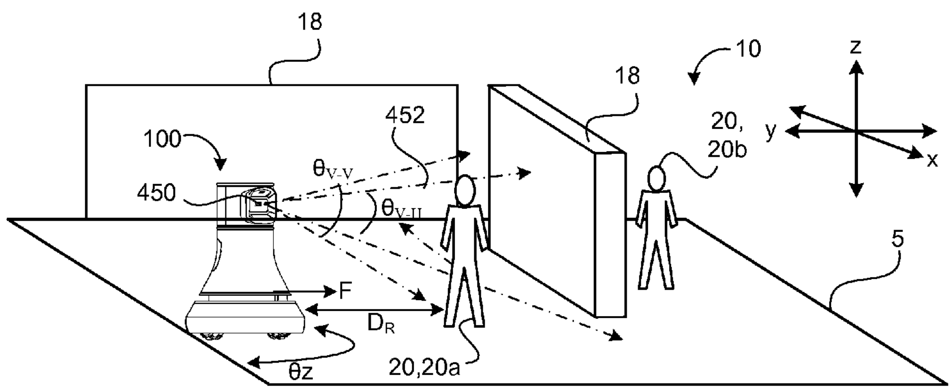

18
10
z
18
452
20,
20b
y
100
θV-V
x
450
θV-H
5
F
DR
θz
20,20a

FIG. 7B

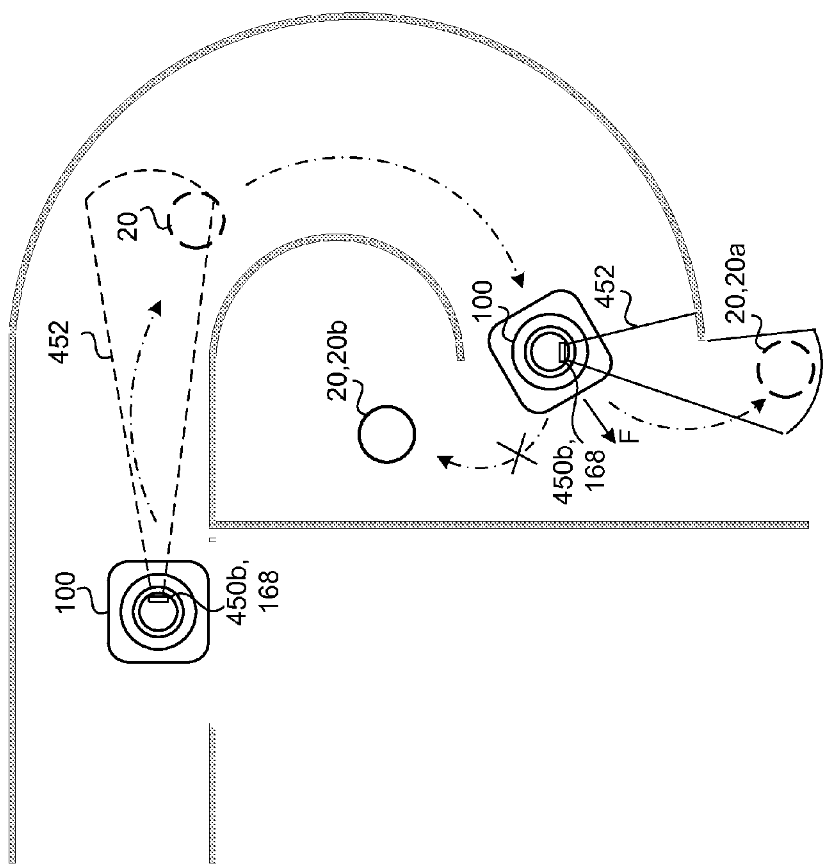



FIG. 8A

Person Detection

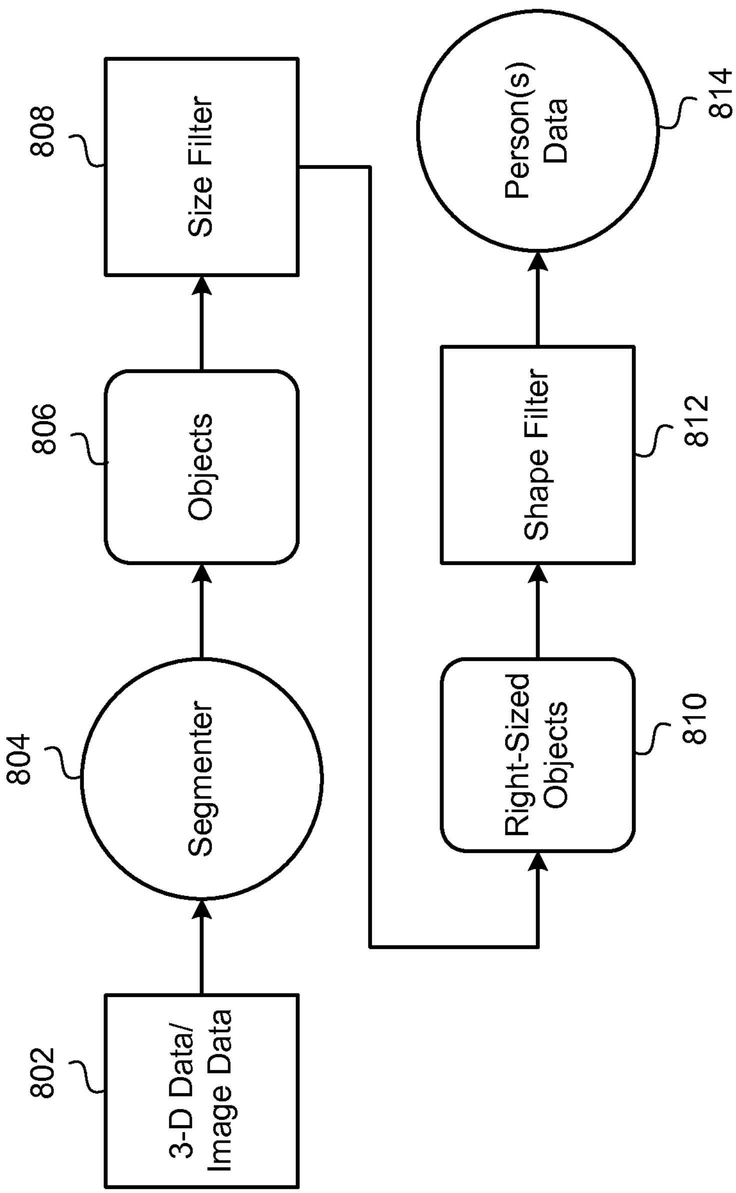



FIG. 8B

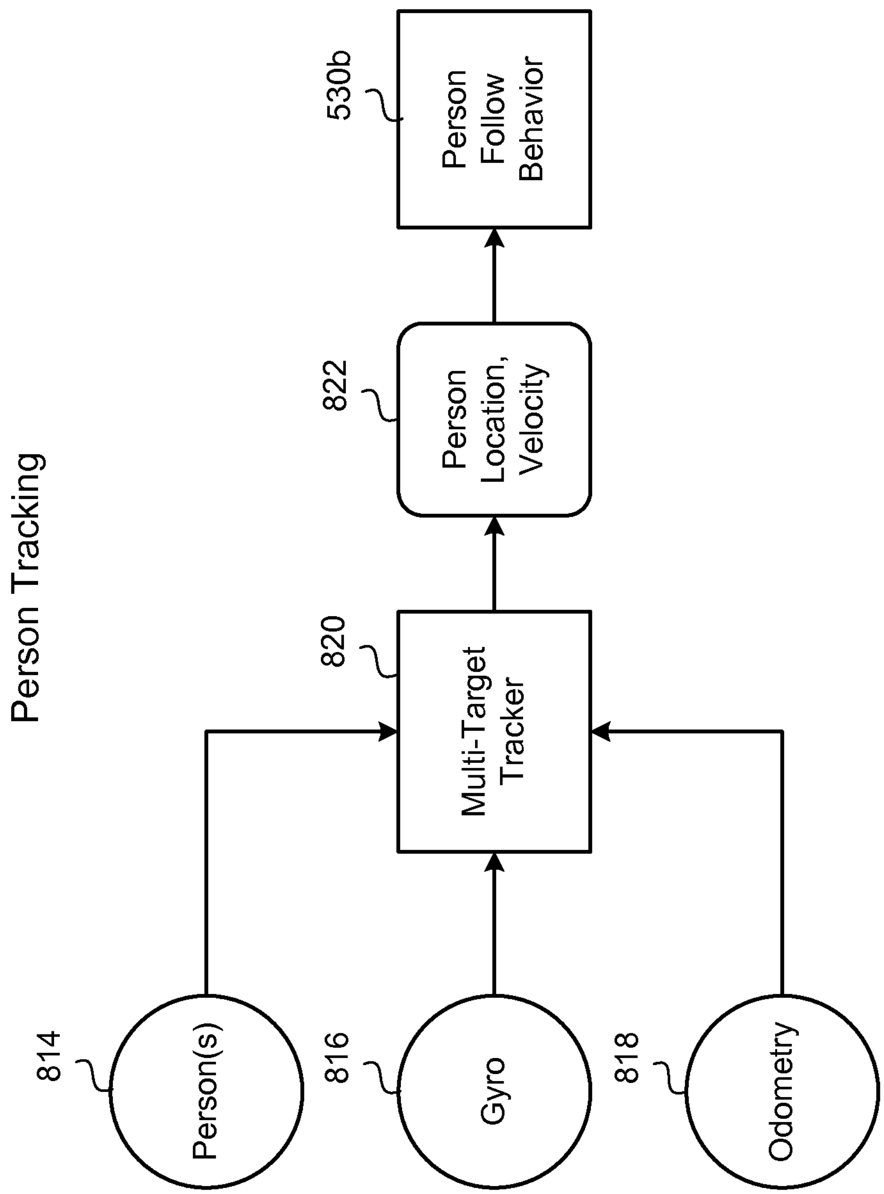

Person Tracking
814
Person(s)
816
Gyro
818
Odometry
820
Multi-Target Tracker
822
Person Location, Velocity
530b
Person Follow Behavior

FIG. 8C

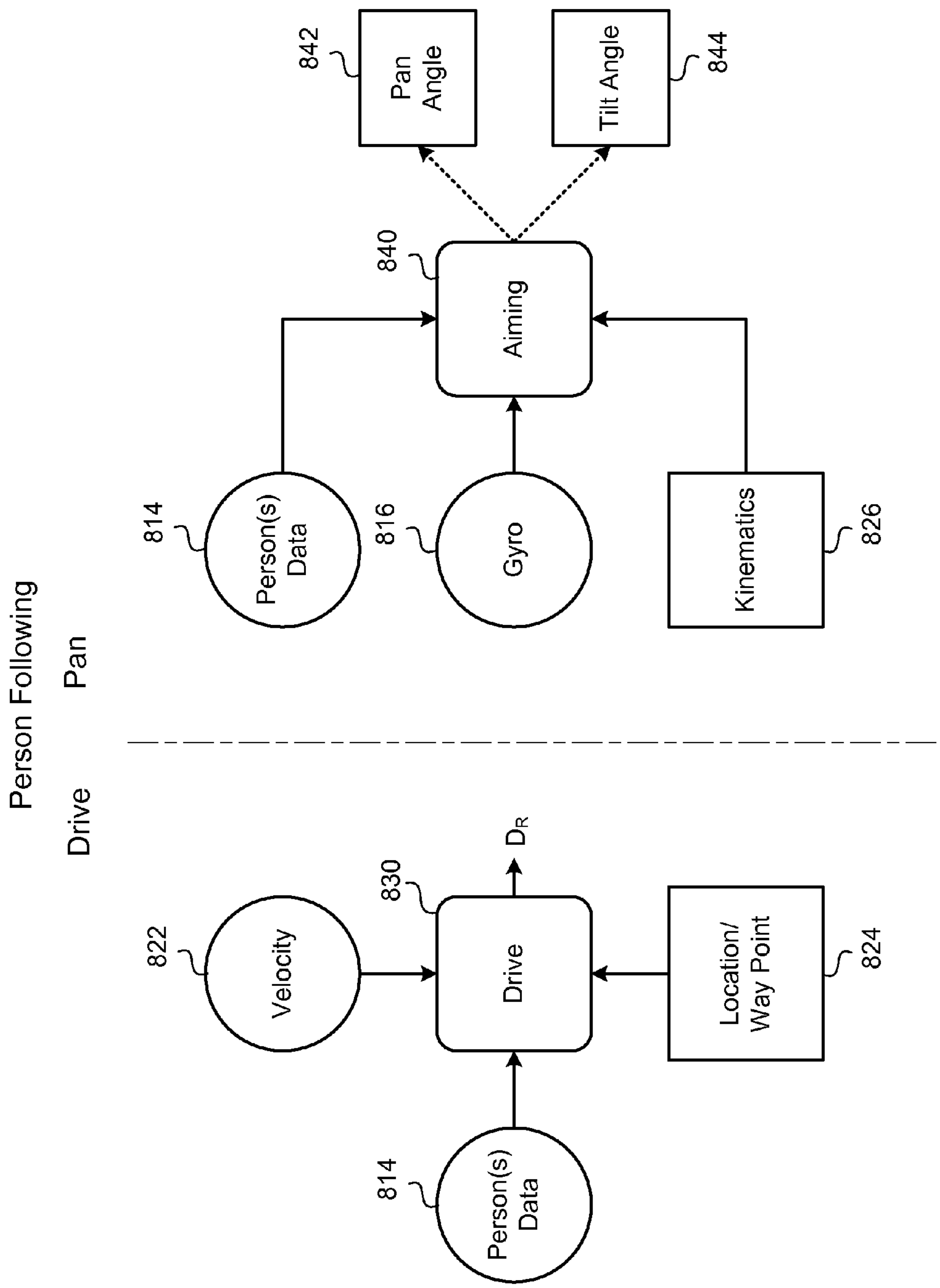

Person Following
Drive
Pan
814
Person(s) Data
822
Velocity
830
Drive
$D_R$
824
Location/ Way Point
814
Person(s) Data
816
Gyro
826
Kinematics
840
Aiming
842
Pan Angle
844
Tilt Angle

FIG. 8D

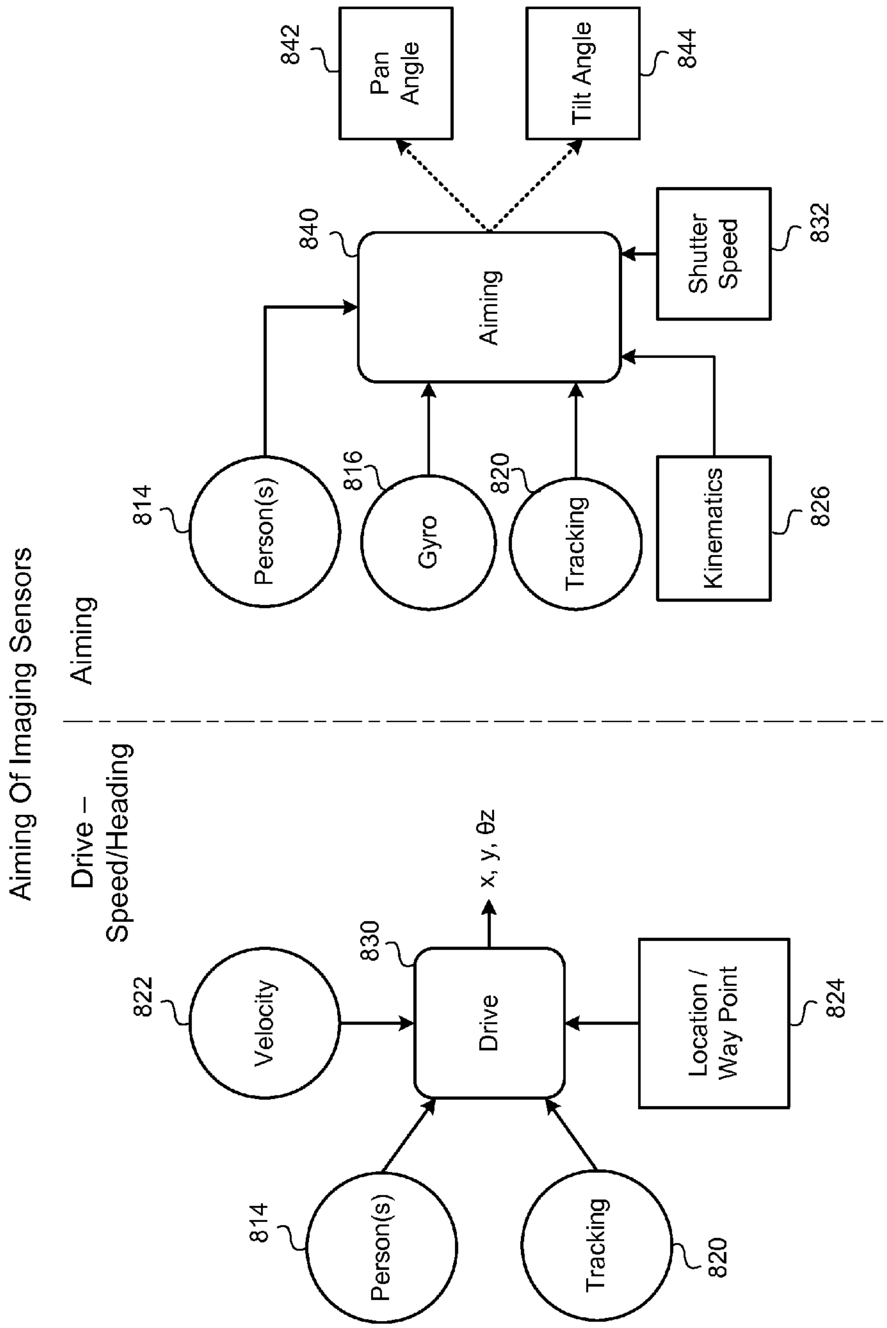

Aiming Of Imaging Sensors
Drive – Speed/Heading
Aiming
Person(s)
814
Tracking
820
Velocity
822
Drive
830
x, y, θz
Location / Way Point
824
Person(s)
814
Gyro
816
Tracking
820
Kinematics
826
Aiming
840
Shutter Speed
832
Pan Angle
842
Tilt Angle
844

FIG. 8E

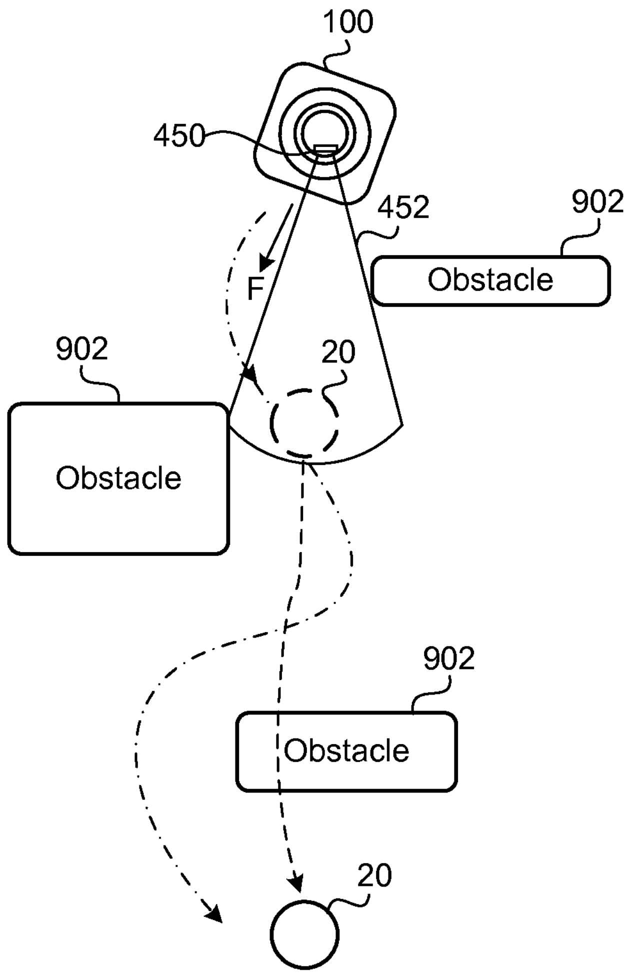



FIG. 9A

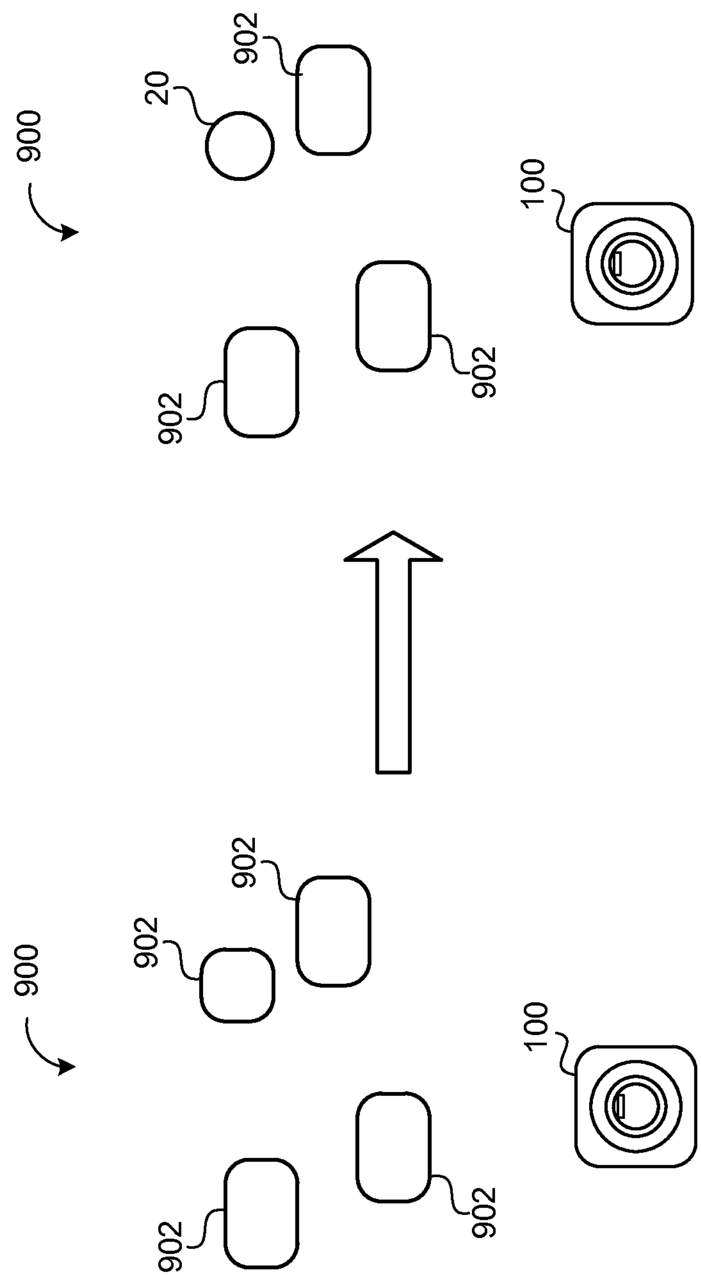



FIG. 9B

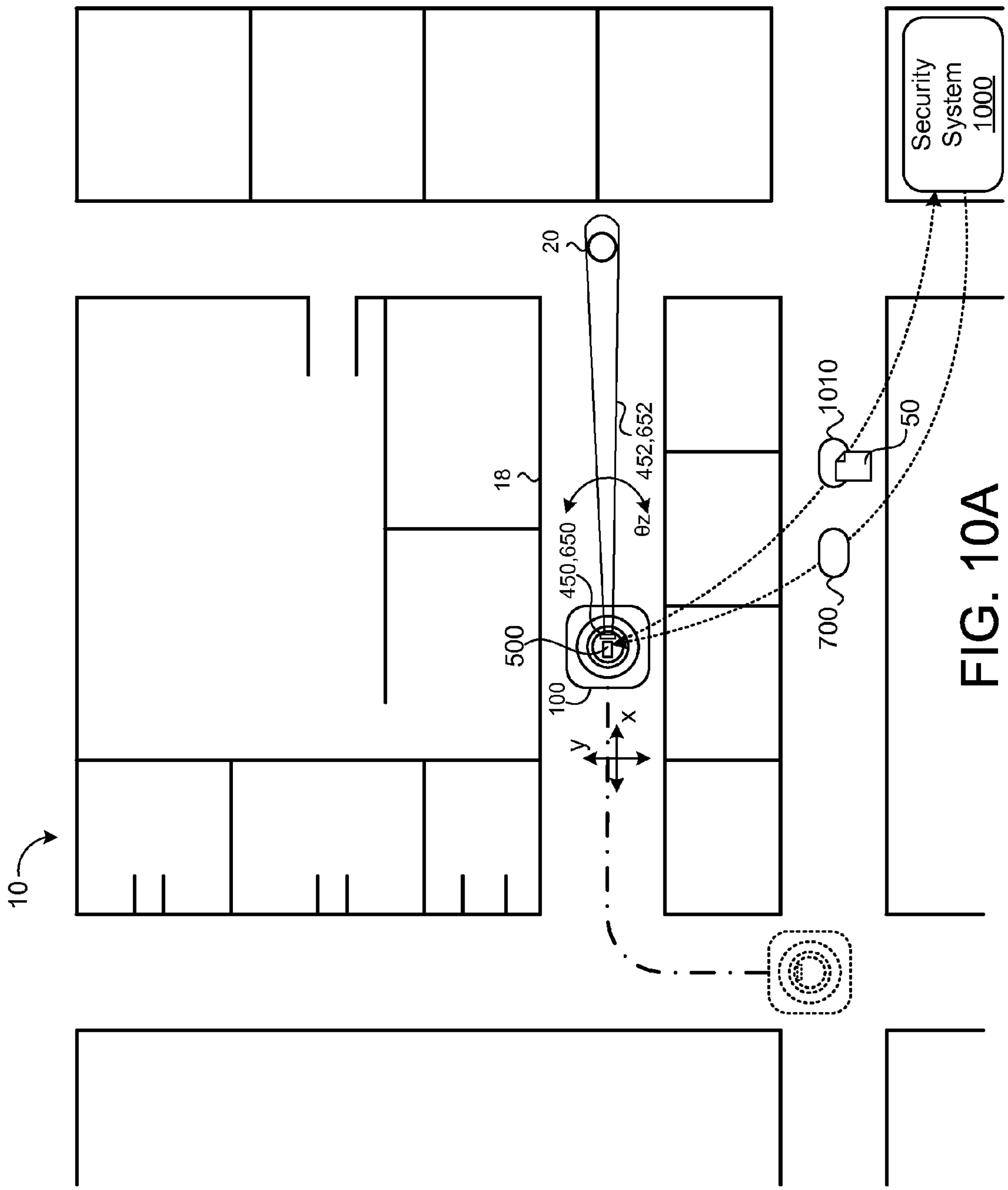

10
18
20
50
100
500
450,650
452,652
θz
x
y
700
1010
Security System 1000

FIG. 10A

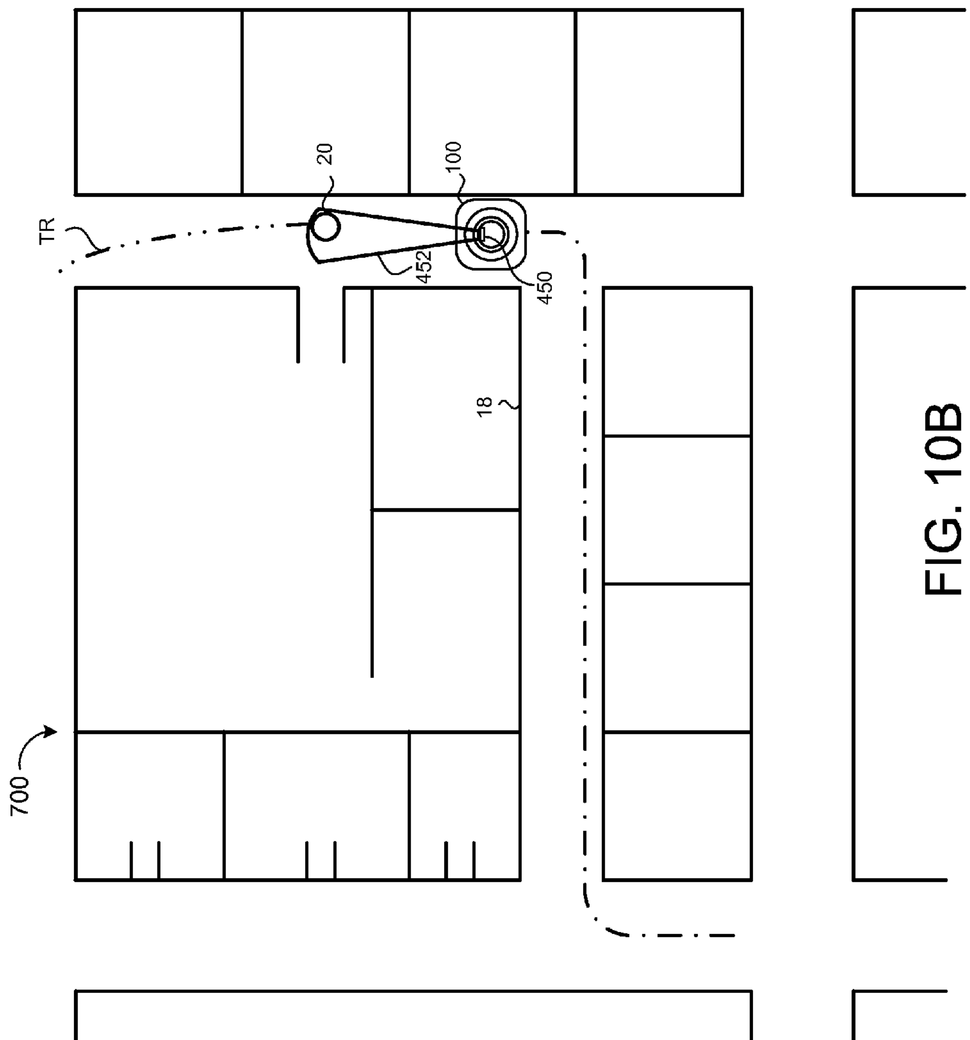



FIG. 10B

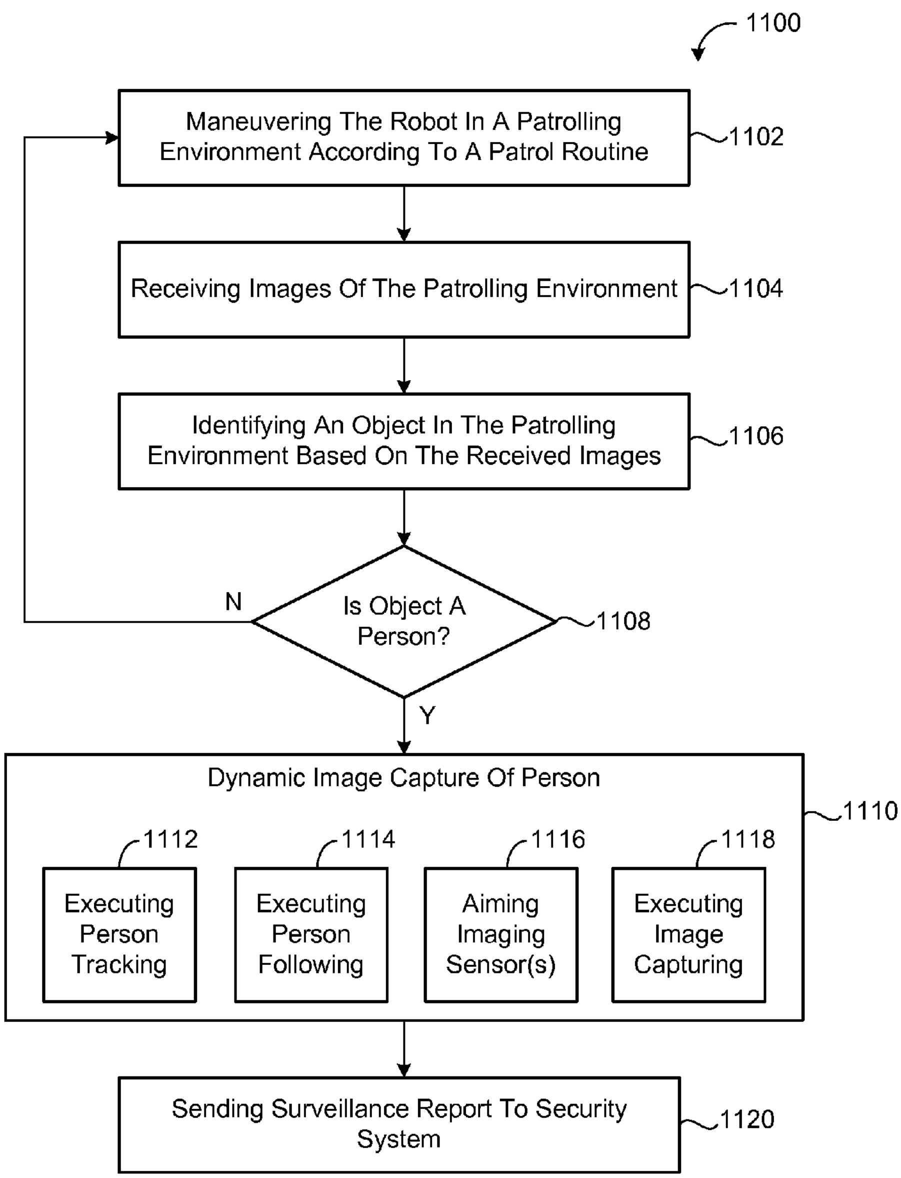

1100
Maneuvering The Robot In A Patrolling Environment According To A Patrol Routine
1102
Receiving Images Of The Patrolling Environment
1104
Identifying An Object In The Patrolling Environment Based On The Received Images
1106
N
Is Object A Person?
1108
Y
Dynamic Image Capture Of Person
1110
1112
Executing Person Tracking
1114
Executing Person Following
1116
Aiming Imaging Sensor(s)
1118
Executing Image Capturing
Sending Surveillance Report To Security System
1120

FIG. 11

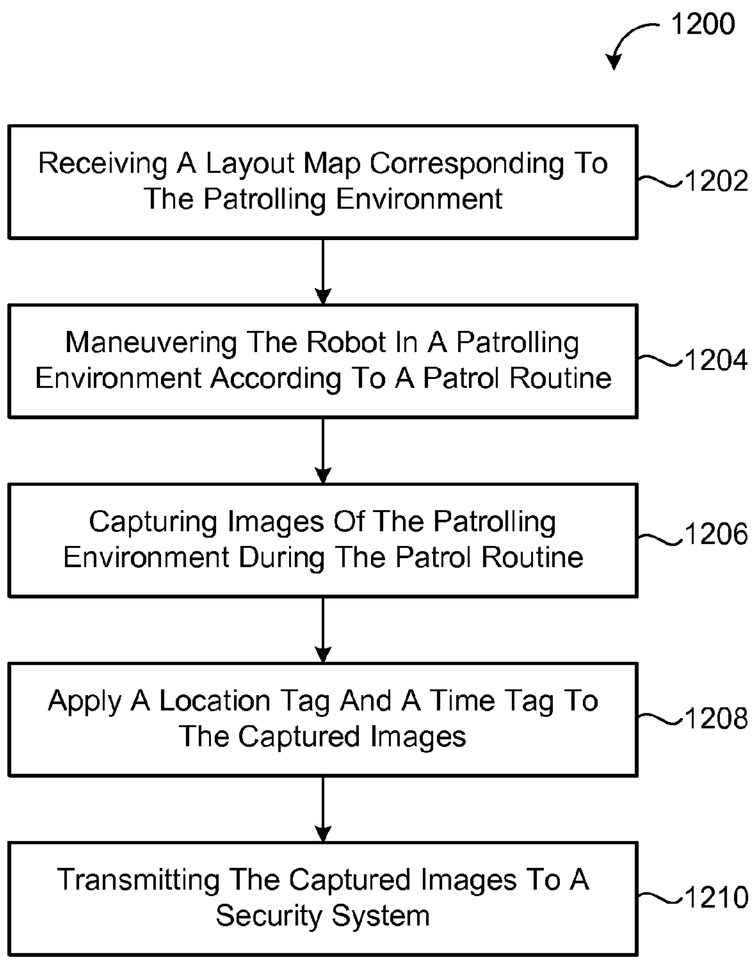

1200
Receiving A Layout Map Corresponding To The Patrolling Environment
1202
Maneuvering The Robot In A Patrolling Environment According To A Patrol Routine
1204
Capturing Images Of The Patrolling Environment During The Patrol Routine
1206
Apply A Location Tag And A Time Tag To The Captured Images
1208
Transmitting The Captured Images To A Security System
1210

FIG. 12A

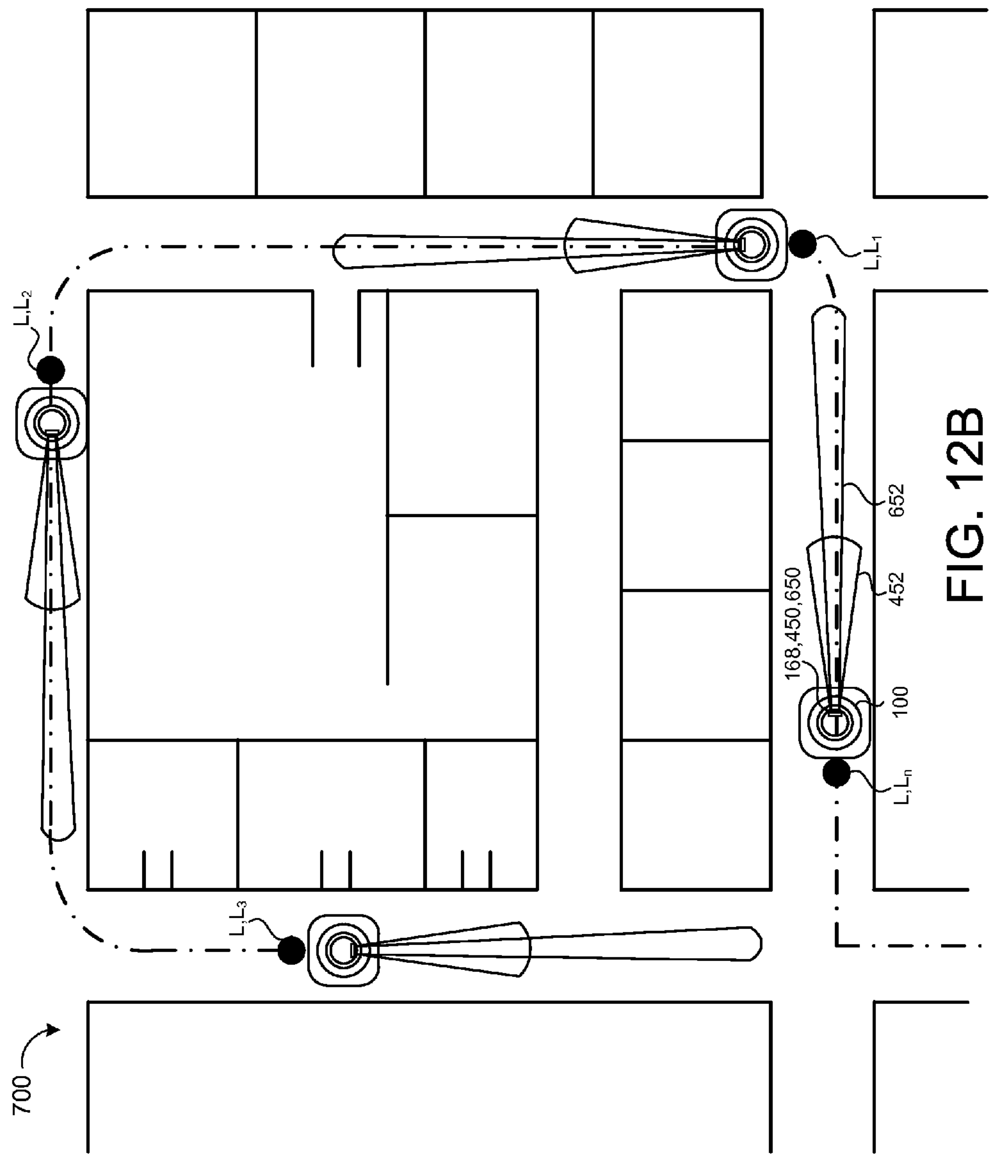



FIG. 12B

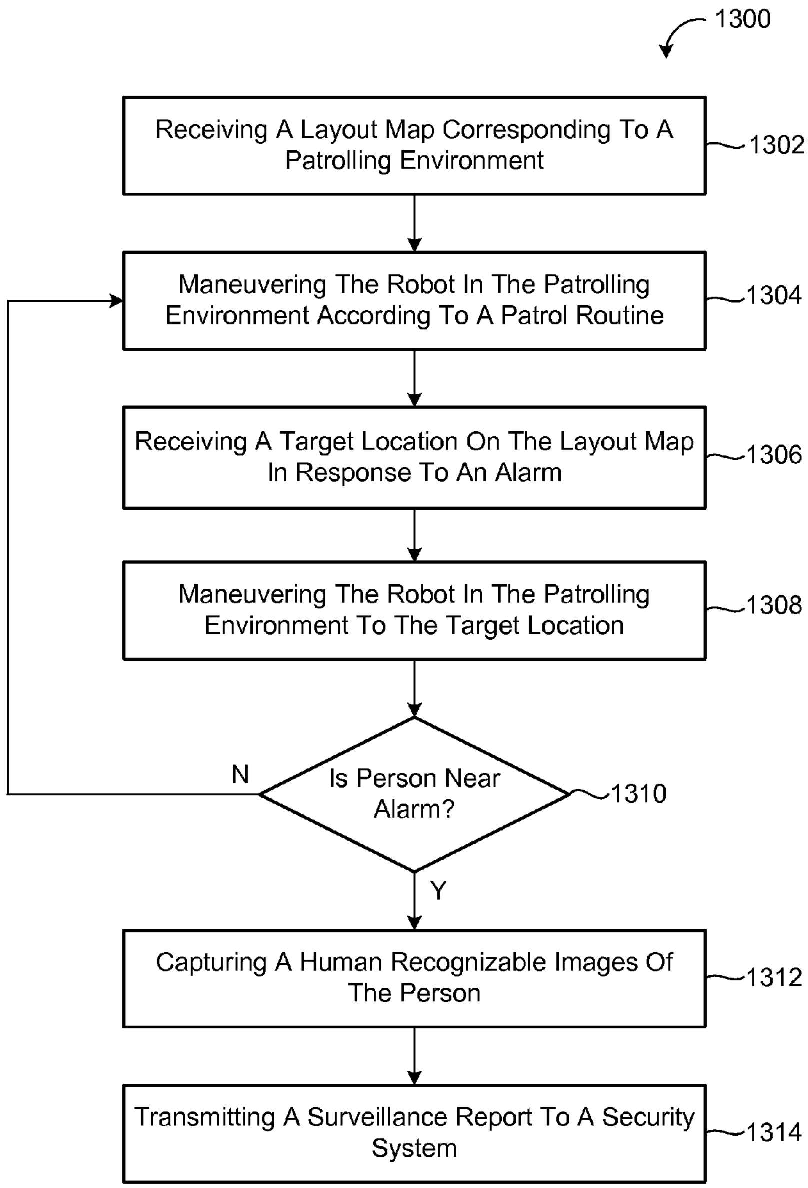
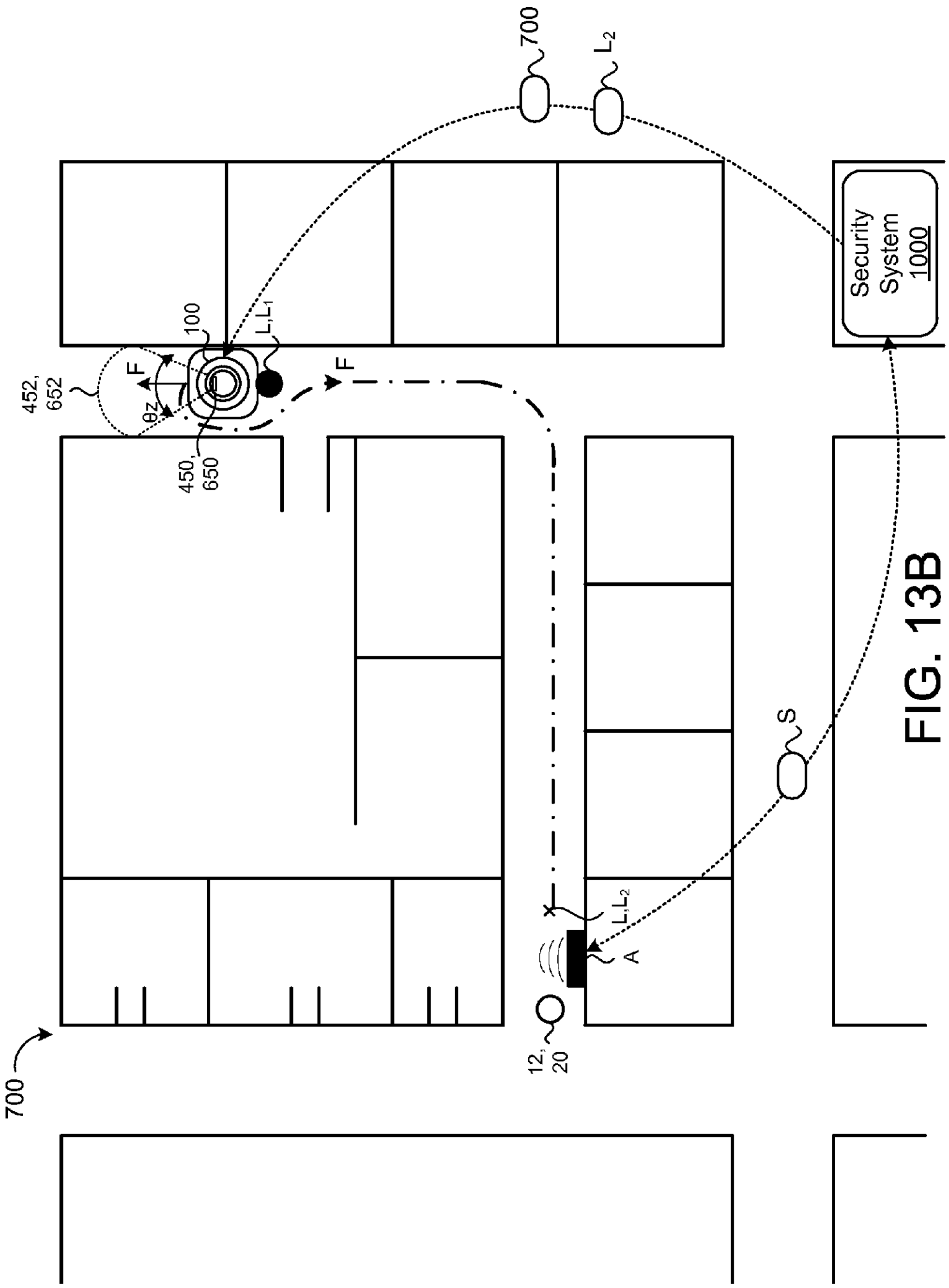

1300
Receiving A Layout Map Corresponding To A Patrolling Environment
1302
Maneuvering The Robot In The Patrolling Environment According To A Patrol Routine
1304
Receiving A Target Location On The Layout Map In Response To An Alarm
1306
Maneuvering The Robot In The Patrolling Environment To The Target Location
1308
Is Person Near Alarm?
1310
N
Y
Capturing A Human Recognizable Images Of The Person
1312
Transmitting A Surveillance Report To A Security System
1314

FIG. 13A



700
L2
Security System 1000
100
L,L1
452, 652
F
θz
450, 650
F
S
L,L2
A
12, 20
700


FIG. 13B

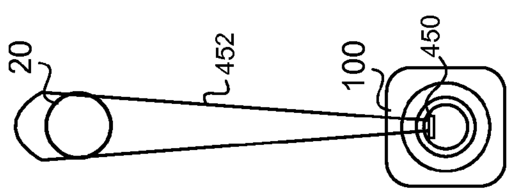



FIG. 14A

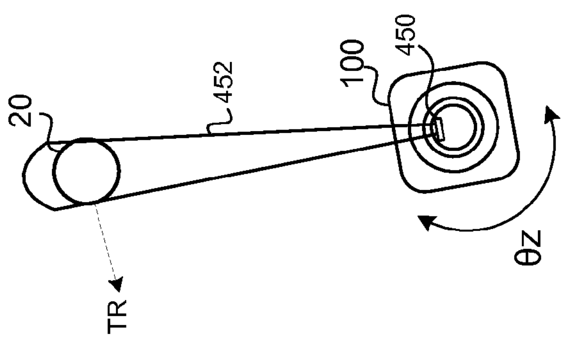



FIG. 14B

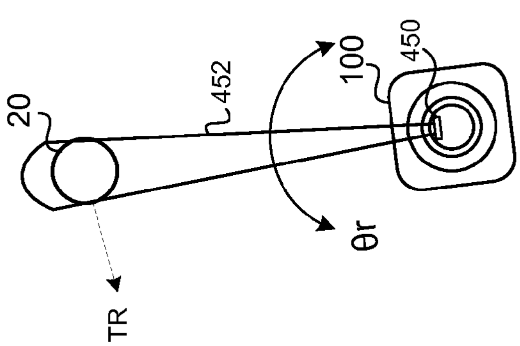



FIG. 14C

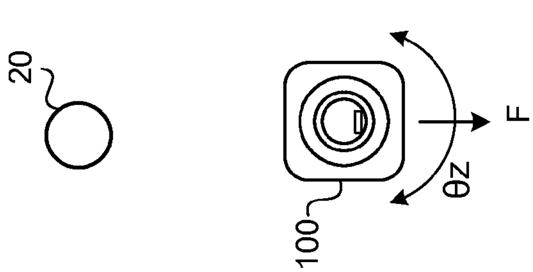



FIG. 14D

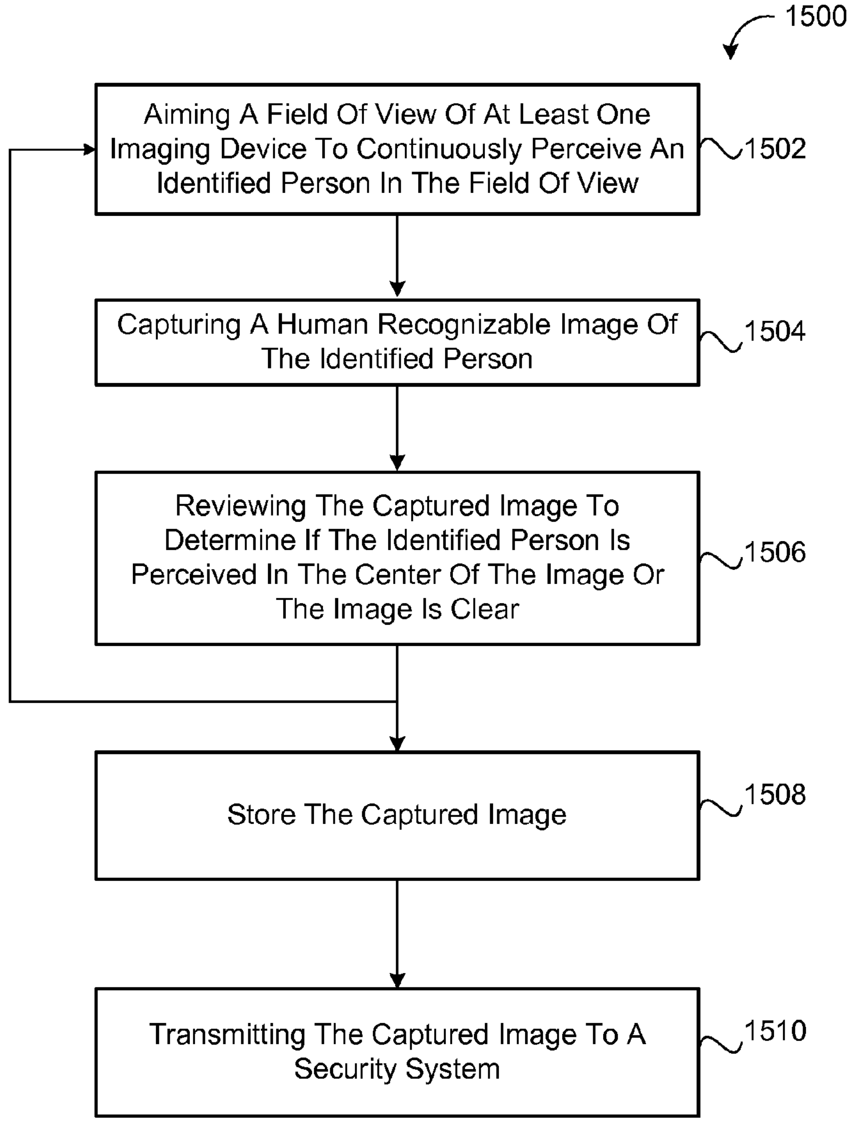

1500
Aiming A Field Of View Of At Least One Imaging Device To Continuously Perceive An Identified Person In The Field Of View
1502
Capturing A Human Recognizable Image Of The Identified Person
1504
Reviewing The Captured Image To Determine If The Identified Person Is Perceived In The Center Of The Image Or The Image Is Clear
1506
Store The Captured Image
1508
Transmitting The Captured Image To A Security System
1510

FIG. 15

# MOBILE SECURITY ROBOT

## CROSS REFERENCE TO RELATED APPLICATION

**[0001]** This U.S. patent application claims priority under 35 U.S.C. §119(e) to U.S. Provisional Application 62/096,747, filed Dec. 24, 2014, which is hereby incorporated by reference in its entirety.

## TECHNICAL FIELD

**[0002]** This disclosure relates to mobile security robots. More specifically, this disclosure relates to mobile security robots using at least one imaging sensor to capture images of ambulating people.

## BACKGROUND

**[0003]** A robot is generally an electro-mechanical machine guided by a computer or electronic programming. Mobile robots have the capability to move around in their environment and are not fixed to one physical location. An example of a mobile robot that is in common use today is an automated guided vehicle or automatic guided vehicle (AGV). An AGV is generally a mobile robot that follows markers or wires in the floor, or uses a vision system or lasers for navigation. Mobile robots can be found in industry, military and security environments.

**[0004]** Some robots use a variety of sensors to obtain data about their surrounding environments, for example, for navigation or obstacle detection and person following. Moreover, some robots use imaging sensors to capture still images or video of objects in their surrounding environments. For example, a robot may patrol an environment and capture images of unauthorized people in its environment using an imaging sensor. The combination of people in motion and dynamics of the robot, however, can pose complications in obtaining acceptable images for recognizing the moving people in the images. For example, a moving person may be outside the center of an image or the combined motion of the robot and the person the robot is photographing may cause the resulting image to be blurred.

## SUMMARY

**[0005]** A security service may use a mobile robot to patrol an environment under surveillance. While patrolling, the robot may use one or more proximity sensors and/or imaging sensors to sense objects in the environment and send reports detailing the sensed objects to one or more remote recipients (e.g., via email over a network). When the robot detects a moving object, the robot may consider a dynamic state of the robot, a dynamic state of the object, and limitations of the imaging sensor to move the robot itself or portion thereof supporting the imaging sensor to aim the imaging sensor relative to the object so as to capture a crisp and clear still image or video of the object. Moreover, the robot may try to determine if the object is a person, for example, by assuming that a moving object is a person, and whether to follow the person to further investigate activities of the person. While aiming the imaging sensor, the robot may try to center the object/person perceived by the imaging sensor in the center of captured images or video. The robot may account for dynamics of the person, such as a location, heading, trajectory and/or velocity of the person, as well as dynamics of the robot, such as holonomic motion and/or lateral velocity, to maneuver the robot and/or aim the at least one imaging sensor to continuously perceive the person within a corresponding field of view of the imaging sensor so that the person is centered in the captured image and the image is clear.

**[0006]** In some implementations, the mobile robot is used in conjunction with a security system. For instance, the security system may communicate with the robot over a network to notify the robot when a disturbance, such as an alarm or unusual activity, is detected in the environment by the security system at a specified location. When notified of the disturbance, the robot may abort a current patrolling routine and maneuver to the specified location to investigate whether or not a trespasser is present. In some examples, the robot communicates with the security system over the network to transmit a surveillance report to the security system (e.g., as an email). The surveillance report may include information regarding a current state of the robot (e.g., location, heading, trajectory, etc.) and/or one or more successive still images or video captured by the imaging sensor. Moreover, the robot may tag each image or video with a location and/or time stamp associated with the capturing of the image or video.

**[0007]** One aspect of the disclosure provides a method of operating a mobile robot. The method includes receiving, at a computing device, a layout map corresponding to a patrolling environment and maneuvering the robot in the patrolling environment based on the received layout map. The method also includes receiving, at the computing device, imaging data of a scene about the robot when the robot maneuvers in the patrolling environment. The imaging data is received from at least one imaging sensor disposed on the robot and is in communication with the computing device. The method further includes identifying, by the computing device, a person in the scene based on the received imaging data, aiming, by the computing device, a field of view of the at least one imaging sensor to continuously perceive the identified person in the field of view based on robot dynamics, person dynamics, and dynamics of the at least one imaging sensor, and capturing, by the computing device, a human recognizable image of the identified person using the at least one imaging sensor.

**[0008]** Implementations of the disclosure may include one or more of the following optional features. In some implementations, the method includes segmenting, by the computing device, the received imaging data into objects and filtering, by the computing device, the objects to remove objects greater than a first threshold size and smaller than a second threshold size. The method further includes identifying, by the computing device, the person in the scene corresponding to at least a portion of the filtered objects. Additionally or alternatively, the first threshold size includes a first height of about 8 feet and the second threshold size includes a second height of about 3 feet.

**[0009]** In some examples, the method includes at least one of at least panning or tilting, by the computing device, the at least one imaging sensor to maintain the corresponding aimed field of view on a facial region of the identified person, or commanding, by the computing device, holonomic motion of the robot to maintain the aimed field of view of the at least one imaging sensor on the facial region of the identified person. The method may include using, by the computing device, a Kalman filter to track and propagate a movement trajectory of the identified person. Additionally or alternatively, the method includes commanding, by the computing device, the robot to move in a planar direction with three planar degrees

of freedom while maintaining the aimed field of view of the at least one imaging sensor on the identified person associated with the movement trajectory. The robot may move in the planar direction at a velocity proportional to the movement trajectory of the identified person.

**[0010]** The method may further include commanding, by the computing device, at least one of panning or tilting the at least one imaging sensor to maintain the aimed field of view of the at least one imaging sensor on the identified person associated with the movement trajectory. Additionally or alternatively, at least one of the commanded panning or tilting is at a velocity proportional to the movement trajectory of the identified person. The velocity of the at least one of panning or tilting may be further proportional to a planar velocity of the robot.

**[0011]** In some examples, the method includes reviewing, by the computing device, the captured image to determine whether or not the identified person is perceived in the center of the image or the image is clear. When the identified person is perceived in the center of the image and the image is clear, the method includes storing the captured image in non-transitory memory in communication with the computing device and transmitting, by the computing device, the captured image to a security system in communication with the computing device. When the identified person is perceived outside the center of the image or the image is blurred, the method includes re-aiming the field of view of the at least one imaging sensor to continuously perceive the identified person in the field of view and capturing a subsequent human recognizable image of the identified person using the at least one imaging sensor.

**[0012]** In some implementations, the method includes applying, by the computing device, a location tag to the captured image associated with a location of the identified person and applying, by the computing device, a time tag associated with a time the image was captured. The location tag may define a location on the layout map. The location tag may define a location based on at least one of robot odometry, waypoint navigation, dead-reckoning, or a global positioning system. At least one imaging sensor may include at least one of a still-image camera, a video camera, a stereo camera, or a three-dimensional point cloud imaging sensor.

**[0013]** The robot dynamics may include an acceleration/deceleration limit of a drive system of the robot. For example, the robot dynamics may include an acceleration/deceleration limit associated with a drive command and a deceleration limit associated with a stop command. In some examples, the person dynamics includes a movement trajectory of the person. Moreover, the dynamics of the at least one imaging sensor may include a latency between sending an image capture request to the at least one imaging sensor and the at least one imaging sensor capturing an image. In some examples, the dynamics of the at least one imaging sensor includes a threshold rotational velocity of the imaging sensor relative to an imaging target to capture a clear image of the imaging target.

**[0014]** Another aspect of the disclosure provides a robot. This aspect may include one or more of the following optional features. The robot includes a robot body, a drive system, at least one imaging sensor disposed on the robot body and a controller in communication with the drive system and the at least one imaging sensor. The drive system has a forward driving direction, supports the robot body and is configured to maneuver the robot over a floor surface of a patrolling environment. The controller receives a layout map corresponding to a patrolled environment, issues drive commands to the drive system to maneuver the robot in the patrolling environment based on the received layout map and receives imaging data from the at least one imaging sensor of a scene about the robot when the robot maneuvers in the patrolling environment. The controller further identifies a moving target in the scene based on the received imaging data, aims a field of view of the at least one imaging sensor to continuously perceive the identified target in the field of view and captures a human recognizable image of the identified target using the at least one imaging sensor. The controller may further segment the received imaging data into objects, filter the objects to remove objects greater than a first threshold size and smaller than a second threshold size and identify a person in the scene as the identified target corresponding to at least a portion of the filtered objects. Additionally or alternatively, the first threshold size may include a first height of about 8 feet and the second threshold size may include a second height of about 3 feet.

**[0015]** In some examples, the robot further includes a rotator and a tilter disposed on the robot body in communication with the controller, the rotator and tilter providing at least one of panning and tilting of the at least one imaging sensor. The controller may command the rotator or tilter to at least one of pan or tilt the at least one imaging sensor to maintain the corresponding aimed field of view on a facial region of the identified person or issue drive commands to the drive system to holonomically move the robot to maintain the aimed field of view of the at least one imaging sensor on the facial region of the identified person. The controller may propagate a movement trajectory of the identified person based on the received imaging data. Additionally or alternatively, the controller may command the drive system to drive in a planar direction with three planar degrees of freedom while maintaining the aimed field of view of the at least one imaging sensor on the identified person associated with the movement trajectory. The drive system may drive in the planar direction at a velocity proportional to the movement trajectory of the identified target.

**[0016]** In some examples, the robot further includes a rotator and a tilter disposed on the robot body and in communication with the controller. The rotator and tilter provides at least one of panning and tilting of the at least one imaging sensor, wherein the controller commands the rotator or the tilter to at least one of pan or tilt the at least one imaging sensor to maintain the aimed field of view of the at least one imaging sensor on the identified target associated with the movement trajectory. Additionally or alternatively, the at least one of the commanded panning or tilting is at a velocity proportional to the movement trajectory of the identified target. The velocity of the at least one of panning or tilting may be further proportional to a planar velocity of the robot.

**[0017]** In some examples, the controller reviews the captured image to determine whether the identified target is perceived in the center of the image or the image is clear. When the identified target is perceived in the center of the image and the image is clear, the controller stores the captured image in non-transitory memory in communication with the computing device and transmits the captured image to a security system in communication with the controller. When the identified target is perceived outside the center of the image or the image is blurred, the controller re-aims the field of view of the at least one imaging sensor to continuously perceive the identified target in the field of view and captures a subsequent human recognizable image of the identified target using the at least one imaging sensor. In some implementations, the controller applies a location tag to the captured image associated with a location of the identified target and applies a time tag associated with a time the image was captured. Additionally or alternatively, the location tag defines a location on the layout map. The location tag may further define a location based on at least one of robot odometry, waypoint navigation, dead-reckoning, or a global positioning system. The at least one imaging sensor may include at least one of a still-image camera, a video camera, a stereo camera, or a three-dimensional point cloud imaging sensor.

**[0018]** In some implementations, the controller aims the at least one imaging sensor based on acceleration/deceleration limits of the drive system and a latency between sending an image capture request to the at least one imaging sensor and the at least one imaging sensor capturing an image. The acceleration/deceleration limits of the drive system may include an acceleration/deceleration limit associated with a drive command and a deceleration limit associated with a stop command. The controller may determine a movement trajectory of the identified target and aims the at least one imaging sensor based on the movement trajectory of the identified target. Moreover, the controller may aim the at least one imaging sensor based on a threshold rotational velocity of the at least one imaging sensor relative to identified target to capture a clear image of the identified target.

**[0019]** Yet another aspect of the disclosure provides a second method of operating a mobile robot. This aspect may include one or more of the following optional features. The method includes receiving, at a computing device, a layout map corresponding to a patrolling environment and maneuvering the robot in the patrolling environment based on the received layout map. In response to an alarm in the patrolling environment, the method further includes receiving, at the computing device, a target location from a security system in communication with the computing device. The target location corresponds to a location of the alarm. The method further includes maneuvering the robot in the patrolling environment to the target location, receiving, at the computing device, imaging data of a scene about the robot when the robot maneuvers to the target location and identifying, by the computing device, a moving target in the scene based on the received imaging data. The imaging data received from at least one imaging sensor is disposed on the robot and is in communication with the computing device.

**[0020]** In some implementations, the method includes aiming, by the computing device, a field of view of the at least one imaging sensor to continuously perceive the identified target in the field of view and capturing, by the computing device, a human recognizable image of the identified target using the at least one imaging sensor. The method may also include capturing a human recognizable video stream of the identified target using the at least one imaging sensor. The method may further include at least one of panning or tilting, by the computing device, the at least one imaging sensor to maintain the corresponding aimed field of view on a facial region of the identified target or commanding, by the computing device, holonomic motion of the robot to maintain the aimed field of view of the at least one imaging sensor on the facial region of the identified target.

**[0021]** In some examples, the method includes using, by the computing device, a Kalman filter to track and propagate a movement trajectory of the identified target and issuing, by the computing device, a drive command to drive the robot within a following distance of the identified target based at least in part on the movement trajectory of the identified target. The drive command may include a waypoint drive command to drive the robot within a following distance of the identified target.

**[0022]** The target location defines one of a location on the layout map or a location based on at least one of robot odometry, waypoint navigation, dead-reckoning, or a global positioning system. The method may further include capturing, by the computing device, human recognizable images about the scene of the robot using the at least one imaging sensor while the robot maneuvers in the patrolling environment.

**[0023]** The method may further include at least one of aiming, by the computing device, a field of view of the at least one imaging sensor in a direction substantially normal to a forward drive direction of the robot or scanning, by the computing device, the field of view of the at least one imaging sensor to increase the corresponding field of view. The human recognizable images may be captured during repeating time cycles and at desired locations in the patrolling environment.

**[0024]** In some implementations, the method includes aiming the at least one imaging sensor to perceive the identified target based on acceleration/deceleration limits of the drive system and a latency between sending an image capture request to the at least one imaging sensor and the at least one imaging sensor capturing an image. The acceleration/deceleration limits of the drive system may include an acceleration/deceleration limit associated with a drive command and a deceleration limit associated with a stop command. The method may include determining a movement trajectory of the identified target and aiming the at least one imaging sensor based on the movement trajectory of the identified target. Moreover, the method may include aiming the at least one imaging sensor based on a threshold rotational velocity of the at least one imaging sensor relative to identified target to capture a clear image of the identified target.

**[0025]** 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

**[0026]** FIG. **1**A is a schematic view of an example robot interacting with an observed person and communicating with a security system.

**[0027]** FIG. **1**B is a schematic view of an example surveillance report.

**[0028]** FIG. **2**A is a perspective view of an exemplary mobile robot.

**[0029]** FIG. **2**B is a perspective view of an exemplary robot drive system.

**[0030]** FIG. **2**C is a front perspective view of another exemplary robot.

**[0031]** FIG. **2**D is a rear perspective view of the robot shown in FIG. **2**C.

**[0032]** FIG. **2**E is side view of the robot shown in FIG. **2**C.

**[0033]** FIG. **2**F is a front view of an exemplary robot having a detachable tablet computer.

**[0034]** FIG. **2**G is a front perspective view of an exemplary robot having an articulated head and mounted tablet computer.

**[0035]** FIG. **3**A is a perspective view of an exemplary robot having a sensor module.

**[0036]** FIG. **3**B is a perspective view of an exemplary sensor module.

**[0037]** FIG. **3**C is a schematic view of an exemplary sensor module.

**[0038]** FIG. **4** provides a schematic view of exemplary robot control flow to and from a controller.

**[0039]** FIG. **5** is a schematic view of an exemplary control system executed by a controller of a mobile robot.

**[0040]** FIG. **6**A is a top view of an exemplary mobile robot having a torso rotating with respect to its base.

**[0041]** FIG. **6**B is a top view of an exemplary mobile robot having a long range imaging sensor.

**[0042]** FIG. **7**A is a schematic view of an exemplary occupancy map.

**[0043]** FIG. **7**B is a schematic view of an exemplary mobile robot having a field of view of a scene in a patrolling area.

**[0044]** FIG. **8**A is a schematic view of an exemplary mobile robot following a person.

**[0045]** FIG. **8**B is a schematic view of an exemplary person detection routine for a mobile robot.

**[0046]** FIG. **8**C is a schematic view of an exemplary person tracking routine for a mobile robot.

**[0047]** FIG. **8**D is a schematic view of an exemplary person following routine for a mobile robot.

**[0048]** FIG. **8**E is a schematic view of an exemplary aiming routine for aiming a field of view of at least one imaging sensor of a mobile robot.

**[0049]** FIG. **9**A is a schematic view of an exemplary mobile robot following a person around obstacles.

**[0050]** FIG. **9**B is a schematic view of an exemplary local map of a mobile robot being updated with a person location.

**[0051]** FIG. **10**A is a schematic view of an exemplary patrolling environment for a mobile robot in communication with a security system.

**[0052]** FIG. **10**B is a schematic view of an exemplary layout map corresponding to an example patrolling environment of a mobile robot.

**[0053]** FIG. **11** provides an exemplary arrangement of operations for operating an exemplary mobile robot to navigate about a patrolling environment using a layout map.

**[0054]** FIG. **12**A provides an exemplary arrangement of operations for operating an exemplary mobile robot to navigate about a patrolling environment using a layout map and obtain human recognizable images in a scene of the patrolling environment.

**[0055]** FIG. **12**B is a schematic view of an exemplary layout map corresponding to an example patrolling environment of a mobile robot.

**[0056]** FIG. **13**A provides an exemplary arrangement of operations for operating an exemplary mobile robot when an alarm is triggered while the mobile robot navigates about a patrolling environment using a layout map.

**[0057]** FIG. **13**B is a schematic view of an exemplary layout map corresponding to a patrolling environment of a mobile robot.

**[0058]** FIG. **14**A is a schematic view of an exemplary mobile robot having a field of view associated with an imaging sensor aimed to perceive a person within the field of view.

**[0059]** FIG. **14**B is a schematic view of an exemplary mobile holonomically moving to maintain an aimed field of view of an imaging sensor perceived on a moving person.

**[0060]** FIG. **14**C is a schematic view of an exemplary mobile robot turning its neck and head to maintain an aimed field of view of an imaging sensor to perceive a moving person.

**[0061]** FIG. **14**D is a schematic view of an exemplary mobile robot driving away from a person after capturing a human recognizable image of the person.

**[0062]** FIG. **15** provides an exemplary arrangement of operations for capturing one or more images of a person identified in a scene of a patrolling environment of an exemplary mobile robot.

**[0063]** Like reference symbols in the various drawings indicate like elements.

## DETAILED DESCRIPTION

**[0064]** Mobile robots can maneuver within environments to provide security services that range from patrolling to tracking and following trespassers. In the example of patrolling, a mobile robot can make rounds within a facility to monitor activity and serve as a deterrence to potential trespassers. For tracking and following, the mobile robot can detect a presence of a person, track movement and predict trajectories of the person, follow the person as he/she moves, capture images of the person and relay the captured images and other pertinent information (e.g., map location, trajectory, time stamp, text message, email communication, aural wireless communication, etc.) to a remote recipient.

**[0065]** Referring to FIG. **1**A, a robot **100** patrolling an environment **10** may sense the presence of a person **20** within that environment **10** using one or more sensors, such as a proximity sensor **410** and/or an imagining sensor **450** of a sensor module **300** in communication with a controller system **500** (also referred to as a controller) of the robot **100**. The robot **100** may maneuver to have the person **20** within a sensed volume of space S and/or to capture images **50** (e.g., still images or video) of the person **20** using the imaging sensor **450**. The controller **500** may tag the image **50** with a location and/or a time associated with capturing the image **50** of the person **20** and transmit the tagged image **50** in a surveillance report **1010** to a security system **1000**. For example, the robot **100** may send the surveillance report **1010** as an email, a text message, a short message service (SMS) message, or an automated voice mail over a network **102** to the remote security system **1000**. Other types of messages are possible as well, which may or may not be sent using the network **102**.

**[0066]** Referring to FIG. **1**B, in some implementations, the surveillance report **1010** includes a message portion **1012** and an attachments portion **1014**. The message portion **1012** may indicate an origination of the surveillance report **1010** (e.g., from a particular robot **100**), an addressee (e.g., an intended recipient of the surveillance report **1010**), a date-time stamp, and/or other information. The attachments portion **1014** may include one or more images **50**, **50***a-b* and/or a layout map **700** showing the current location of the robot **100** and optionally a detected object **12** or person **20**. In some embodiments, the imaging sensor **450** is a camera with a fast shutter speed that rapidly takes successive images **50** of one or more moving targets and batches the one or more images **50** for transmission.

**[0067]** While conventional surveillance cameras can be placed along walls or ceilings within the environment **10** to capture images within the environment **10**, it is often very difficult, and sometimes impossible, to recognize trespassers in the image data due to limitations inherent to these conventional surveillance cameras. For instance, due to the placement and stationary nature of wall and/or ceiling mounted surveillance cameras, people **20** are rarely centered within the captured images and the images are often blurred when the people **20** are moving through the environment **10**. Additionally, an environment **10** may often include blind spots where surveillance cameras cannot capture images **50**. The robot **100** shown in FIGS. **1**A and **1**B may resolve the aforementioned limitations found in conventional surveillance cameras by maneuvering the robot **100** to capture image data **50** (e.g., still images or video) of the person **20** along a field of view **452** (FIG. **3**B) of the imaging sensor **450** while patrolling the environment **10**. The controller **500** may account for dynamics of the person **20** (e.g., location, heading, trajectory, velocity, etc.), shutter speed of the imaging sensor **450** and dynamics of the robot **100** (e.g., velocity/holonomic motion) to aim the corresponding field of view **452** of the imaging sensor **450** to continuously perceive the person **20** within the field of view **452**, so that the person **20** is centered in the captured image **50** and the image **50** is clear. The controller system **500** may execute movement commands to maneuver the robot **100** in relation to the location of the person **20** to capture a crisp image **50** of a facial region of the person **20**, so that the person **20** is recognizable in the image **50**. Surveillance reports **1010** received by the security system **1000** that include images **50** depicting the facial region of the person **20** may be helpful for identifying the person **20**. The movement commands may be based on a trajectory prediction TR and velocity of the person **20**, in addition to dynamics of the robot **100** and/or shutter speed of the imaging sensor **450**. The controller **500** integrates the movements of the robot **100**, the person **20**, and the shutter speed and/or focal limitations of the imaging sensor **450** so that the robot **100** accelerates and decelerates to accommodate for the velocity of the person **20** and the shutter speed and/or focal limitations of the imaging sensor **450** while positioning itself to capture an image **50** (e.g., take a picture) of the moving person **20**. The controller **500** predicts the trajectory of the moving person and calculates the stop time and/or deceleration time of the robot **100** and the focal range and shutter speed of the imaging sensor **450** in deciding at which distance from the moving person **20** to capture a photograph or video clip. For instance, when the person **20** is running away from the robot **100**, the controller system **500** may command the robot **100** to speed up ahead of the person **20** so that the person **20** is centered in the field of view **452** of the imaging sensor **450** once the robot **100** slows, stops and/or catches up to the person **20** for capturing a clear image **50**. In other situations, the controller **500** may command the robot **100** to back away from the person **20** if the person **20** is determined to be too close to the imaging sensor **450** to capture a crisp image **50**. Moreover, the controller **500** may command the robot **100** to follow the person **20**, for example, at a distance, to observe the person **20** for a period of time.

**[0068]** FIGS. **2**A-**2**G illustrate example robots **100**, **100***a*, **100***b*, **100***c*, **100***d* that may patrol an environment **10** for security purposes. Other types of robots **100** are possible as well. In the example shown in FIG. **2**A, the robot **100***a* includes a robot body **110** (or chassis) that defines a forward drive direction F. The robot body **110** may include a base **120** and a torso **130** supported by the base **120**. The base **120** may include enough weight (e.g., by supporting a power source **105** (batteries)) to maintain a low center of gravity $CG_B$ of the base **120** and a low overall center of gravity $CG_R$ of the robot **100** for maintaining mechanical stability. The base **120** may support a drive system **200** configured to maneuver the robot **100** across a floor surface **5**. The drive system **200** is in communication with a controller system **500**, which can be supported by the base **120** or any other portion of the robot body **110**. The controller system **500** may include a computing device **502** (e.g., a computer processor) in communication with non-transitory memory **504**.

**[0069]** The controller **500** communicates with the security system **1000**, which may transmit signals to the controller **500** indicating one or more alarms within the patrolling environment **10** and locations associated with the alarms. The security system **1000** may provide a layout map **700** (FIG. **7**B) corresponding to the patrolling environment **10** of the robot **100**. Moreover, the controller **500** may transmit one or more human recognizable images **50** captured by at least one imaging sensor **450** to the security system **1000**, wherein a person **20** can review the captured images **50**. The controller **500** may store the captured images **50** within the non-transitory memory **504**. The security system **1000** may further access the non-transitory memory **504** via the controller **500**. In the examples shown, the robot **100** houses the controller **500**, but in other examples (not shown), the controller **500** can be external to the robot **100** and controlled by a user (e.g., via a handheld computing device).

**[0070]** Referring to FIG. **2**B, in some implementations, the drive system **200** provides omni-directional and/or holonomic motion control of the robot **100**. As used herein the term "omni-directional" refers to the ability to move in substantially any planar direction, including side-to-side (lateral), forward/back, and rotational. These directions are generally referred to herein as x, y, and θz, respectively. Furthermore, the term "holonomic" is used in a manner substantially consistent with the literature use of the term and refers to the ability to move in a planar direction with three planar degrees of freedom—two translations and one rotation. Hence, a holonomic robot has the ability to move in a planar direction at a velocity made up of substantially any proportion of the three planar velocities (forward/back, lateral, and rotational), as well as the ability to change these proportions in a substantially continuous manner.

**[0071]** The robot **100** can operate in human environments (e.g., environments typically designed for bipedal, walking occupants) using wheeled mobility. In some implementations, the drive system **200** includes first, second, third, and fourth drive wheels **210***a*, **210***b*, **210***c*, **210***d*, which may be equally spaced (e.g., symmetrically spaced) about the vertical axis Z; however, other arrangements are possible as well, such as having only two or three drive wheels or more than four drive wheels. Each drive wheel **210***a-d* is coupled to a respective drive motor **220***a*, **220***b*, **220***c*, **220***d* that can drive the drive wheel **210***a-d* in forward and/or reverse directions independently of the other drive motors **220***a-d*. Each drive motor **220***a-d* can have a respective encoder, which provides wheel rotation feedback to the controller **500** system.

**[0072]** Referring again to FIGS. **2**C-**2**G, in some implementations, the torso **130** supports a payload, such as an interface module **140** and/or a sensor module **300**. The interface module **140** may include a neck **150** supported by the torso **130** and a head **160** supported by the neck **150**. The neck **150** may provide panning and tilting of the head **160** with respect to the torso **130**, as shown in FIG. **2**E. In some examples, the neck **150** moves (e.g., telescopically, via articulation, or along a linear track) to alter a height of the head **160**

with respect to the floor surface **5**. The neck **150** may include a rotator **152** and a tilter **154**. The rotator **152** may provide a range of angular movement $\theta_R$ (e.g., about a Z axis) of between about 90 degrees and about 360 degrees. Other ranges are possible as well. Moreover, in some examples, the rotator **152** includes electrical connectors or contacts that allow continuous 360 degree rotation of the neck **150** and the head **160** with respect to the torso **130** in an unlimited number of rotations while maintaining electrical communication between the neck **150** and the head **160** and the remainder of the robot **100**. The tilter **154** may include the same or similar electrical connectors or contacts allowing rotation of the head **160** with respect to the torso **130** while maintaining electrical communication between the head **160** and the remainder of the robot **100**. The tilter **154** may move the head **160** independently of the rotator **152** about a Y axis between an angle $\theta_T$ of ±90 degrees with respect to the Z-axis. Other ranges are possible as well, such as ±45 degrees, etc. The head **160** may include a screen **162** (e.g., touch screen), a microphone **164**, a speaker **166**, and an imaging sensor **168**, as shown in FIG. **2**C. The imaging sensor **168** can be used to capture still images, video, and/or 3D volumetric point clouds from an elevated vantage point of the head **160**.

**[0073]** In some implementations, the head **160** is or includes a fixedly or releasably attached tablet computer **180** (referred to as a tablet), as shown in FIG. **2**F. The tablet computer **180** may include a processor **182**, non-transitory memory **184** in communication with the non-transitory memory **184**, and a screen **186** (e.g., touch screen) in communication with the processor **182**, and optionally I/O (e.g., buttons and/or connectors, such as micro-USB, etc.). An example tablet **180** includes the Apple iPad® by Apple, Inc. In some examples, the tablet **180** functions as the controller system **500** or assists the controller system **500** in controlling the robot **100**.

**[0074]** The tablet **180** may be oriented forward, rearward or upward. In the example shown in FIG. **2**G, the robot **100**, **100***c* includes a tablet **180** attached to a payload portion **170** of the interface module **140**. The payload portion **170** may be supported by the torso **130** and supports the neck **150** and head **160**, for example, in an elevated position, so that the head **160** is between about 4 ft. and 6 ft. above the floor surface **5** (e.g., to allow a person **20** to view the head **160** while looking straight forward at the robot **100**).

**[0075]** Referring to FIGS. **3**A and **3**B, in some implementations, the torso **130** includes a sensor module **300** having a module body **310**. The module body **310** (also referred to as a cowling or collar) may have a surface of revolution that sweeps about a vertical axis of rotation C of the module body **310** (also referred to as a collar axis) with respect to the floor surface **5**. A surface of revolution is a surface in Euclidean space created by rotating a curve (the generatrix) around a straight line (e.g., the Z axis) in its plane. In some examples, the module body **310** defines a three dimensional projective surface of any shape or geometry, such as a polyhedron, circular or an elliptical shape. The module body **310** may define a curved forward face **312** (e.g., of a cylindrically shaped body axially aligned with the base **120**) defining a recess or cavity **314** that houses imaging sensor(s) **450** of the sensor module **300**, while maintaining corresponding field(s) of view **452** of the imaging sensor(s) **450** unobstructed by the module body **310**. Placement of an imaging sensor **450** on or near the forward face **312** of the module body **310** allows the corresponding field of view **452** (e.g., about 285 degrees) to be less than an external surface angle of the module body **310** (e.g., 300 degrees) with respect to the imaging sensor **450**, thus preventing the module body **310** from occluding or obstructing the detection field of view **452** of the imaging sensor **450**. Placement of the imaging sensor(s) **450** inside the cavity **314** conceals the imaging sensor(s) **450** (e.g., for aesthetics, versus having outwardly protruding sensors) and reduces a likelihood of environmental objects snagging on the imaging sensor(s) **450**. Unlike a protruding sensor or feature, the recessed placement of the image sensor(s) **450** reduces unintended interactions with the environment **10** (e.g., snagging on people **20**, obstacles, etc.), especially when moving or scanning, as virtually no moving part extends beyond the envelope of the module body **310**.

**[0076]** In some examples, the sensor module **300** includes a first interface **320***a* and a second interface **320***b* spaced from the first interface **320***a*. The first and second interfaces **320***a*, **320***b* rotatably support the module body **310** therebetween. A module actuator **330**, also referred to as a panning system (e.g., having a panning motor and encoder), may rotate the module body **310** and the imaging sensor(s) **450** together about the collar axis C. All rotating portions of the imaging sensor(s) **450** extend a lesser distance from the collar axis C than an outermost point of the module body **310**.

**[0077]** The sensor module **300** may include one or more imaging sensors **450** of a sensor system **400**. The imaging sensor(s) **450** may be a three-dimensional depth sensing device that directly captures three-dimensional volumetric point clouds (e.g., not by spinning like a scanning LIDAR) and can point or aim at an object that needs more attention. The imaging sensor(s) **450** may reciprocate or scan back and forth slowly as well. The imaging sensor(s) **450** may capture point clouds that are 58 degrees wide and 45 degrees vertical, at up to 60 Hz.

**[0078]** In some implementations, the sensor module **300** includes first, second, and third imaging sensors **450**, **450***a*, **450***b*, **450***c*. Each imaging sensor **450** is arranged to have a field of view **452** centered about an imaging axis **455** directed along the forward drive direction F. In some implementations, one or more imaging sensors **450** are long range sensors having a field of view **452** centered about an imaging axis **455** directed along the forward drive direction F. The first imaging sensor **450***a* is arranged to aim its imaging axis **455***a* downward and away from the torso **130**. By angling the first imaging sensor **450***a* downward, the robot **100** receives dense sensor coverage in an area immediately forward or adjacent to the robot **100**, which is relevant for short-term travel of the robot **100** in the forward direction. The second imaging sensor **450***b* is arranged with its imaging axis **455***b* pointing substantially parallel with the ground along the forward drive direction F (e.g., to detect objects approaching a mid and/or upper portion of the robot **100**). The third imaging sensor **450***c* is arranged to have its imaging axis **455***c* aimed upward and away from the torso **130**.

**[0079]** The robot **100** may rely on one or more imaging sensors **450***a*-*c* more than the remaining imaging sensors **450***a*-*c* during different rates of movement, such as fast, medium, or slow travel. Fast travel may include moving at a rate of 3-10 mph or corresponding to a running pace of an observed person **20**. Medium travel may include moving at a rate of 1-3 mph, and slow travel may include moving at a rate of less than 1 mph. During fast travel, the robot **100** may use the first imaging sensor **450***a*, which is aimed downward to increase a total or combined field of view of both the first and second imaging sensors **450***a*, **450***b*, and to give sufficient time for the robot **100** to avoid an obstacle because higher speeds of travel lengthens reaction time when avoiding collisions with obstacles. During slow travel, the robot **100** may use the third imaging sensor **450***c*, which is aimed upward above the ground **5**, to track a person **20** that the robot **100** is meant to follow. The third imaging sensor **450***c* can be arranged to sense objects as they approach a payload **170** of the torso **130**. In some examples, the one or both of the second and third imaging sensors **450***b*, **450***c* are imaging sensors configured to capture still images and/or video of a person **20** within the field of view **452**.

**[0080]** The captured separate three dimensional volumetric point clouds of the imaging sensors **450***a-c* may be of overlapping or non-overlapping sub-volumes or fields of view **452***a-c* within an observed volume of space S (FIGS. **2**A and **3**B). Moreover, the imaging axes **455***a-c* of the imaging sensors **450***a-c* may be angled with respect to a plane normal to the collar axis C to observe separate sub-volumes **452** of the observed volume of space S. The separate sub-volumes **452** are fields of view that can be displaced from one another along the collar axis C.

**[0081]** The imaging axis **455** of one of the imaging sensors **450***a-c* (e.g., the first imaging axis **455***a* or third imaging axis **455***c*) may be angled with respect to the plane normal to the collar axis C to observe the volume of space S adjacent the robot **100** at a height along the collar axis C that is greater than or equal to a diameter D of the collar **310**.

**[0082]** In some implementations, the torso body **132** supports or houses one or more proximity sensors **410** (e.g., infrared sensors, sonar sensors and/or stereo sensors) for detecting objects and/or obstacles about the robot **100**. In the example shown in FIG. **4**, the torso body **132** includes first, second, and third proximity sensors **410***a*, **410***b*, **410***c* disposed adjacent to the corresponding first, second, and third imaging sensor **450***a*, **450***b*, **450***c* and having corresponding sensing axes **412***a*, **412***b*, **412***c* arranged substantially parallel to the corresponding imaging axes **455***a*, **455***b*, **455***c* of the first, second, and third imaging sensors **450***a*, **450***b*, **450***c*. The sensing axes **412***a*, **412***b*, **412***c* may extend into the torso body **132** (e.g., for recessed or internal sensors). Having the first, second, and third proximity sensors **410***a*, **410***b*, **410***c* arranged to sense along substantially the same directions as the corresponding first, second, and third imaging sensors **450***a*, **450***b*, **450***c* provides redundant sensing and/or alternative sensing for recognizing objects or portions of the local environment **10** and for developing a robust local perception of the robot's environment. Moreover, the proximity sensors **410** may detect objects within an imaging dead zone **453** (FIG. **6**A) of imaging sensors **450**.

**[0083]** The torso **130** may support an array of proximity sensors **410** disposed within the torso body recess **133** and arranged about a perimeter of the torso body recess **133**, for example in a circular, elliptical, or polygonal pattern. Arranging the proximity sensors **410** in a bounded (e.g., closed loop) arrangement, provides proximity sensing in substantially all directions along the drive direction of the robot **100**. This allows the robot **100** to detect objects and/or obstacles approaching the robot **100** within at least a 180 degree sensory field of view along the drive direction of the robot **100**.

**[0084]** In some examples, one or more torso sensors, including one or more imaging sensors **450** and/or proximity sensors **410**, have an associated actuator moving the sensor **410**, **450** in a scanning motion (e.g., side-to side) to increase the sensor field of view **452**. In additional examples, the imaging sensor **450** includes an associated rotating mirror, prism, variable angle micro-mirror, or MEMS mirror array to increase the field of view **452** of the imaging sensor **450**. Mounting the sensors **410**, **450** on a round or cylindrically shaped torso body **132** allows the sensors **410**, **450** to scan in a relatively wider range of movement, thus increasing the sensor field of view **452** relatively greater than that of a flat faced torso body **132**.

**[0085]** Referring to FIG. **3**C, in some examples, the sensor module **300** includes a sensor board **350** (e.g., printed circuit board) having a microcontroller **352** (e.g., processor) in communication with a panning motor driver **354** and a sonar interface **356** for the sonar proximity sensors **410***a-c*. The sensor board **350** communicates with the collar actuator **330** (e.g., panning motor and encoder), the imaging sensor(s) **450**, and the proximity sensor(s) **410**. Each proximity sensor **410** may include a transmit driver **356***a*, a receiver amplifier **356***b*, and an ultrasound transducer **356***c*.

**[0086]** FIG. **4** provides a schematic view of the robot control flow to and from the controller **500**. A robot base application **520** executing on the controller **500** (e.g., executing on a control arbitration system **510***b* (FIG. **5**)) communicates with drivers **506** for communicating with the sensor system **400**. To achieve reliable and robust autonomous movement, the sensor system **400** may include several different types of sensors, which can be used in conjunction with one another to create a perception of the robot's environment sufficient to allow the robot **100** to make intelligent decisions about actions to take in that environment **10**. The sensor system **400** may include one or more types of sensors supported by the robot body **110**, which may include obstacle detection obstacle avoidance (ODOA) sensors, communication sensors, navigation sensors, etc. For example, these sensors may include, but are not limited to, drive motors **220***a-d*, a panning motor **330**, a camera **168** (e.g., visible light and/or infrared camera), proximity sensors **410**, contact sensors, three-dimensional (3D) imaging/depth map sensors **450**, a laser scanner **440** (LIDAR (Light Detection And Ranging, which can entail optical remote sensing that measures properties of scattered light to find range and/or other information of a distant target) or LADAR (Laser Detection and Ranging)), an inertial measurement unit (IMU) **470**, radar, etc.

**[0087]** The imaging sensors **450** (e.g., infrared range sensors or volumetric point cloud sensors) may generate range value data representative of obstacles within an observed volume of space adjacent the robot **100**. Moreover, the proximity sensors **410** (e.g., presence sensors) may generate presence value data representative of obstacles within the observed volume of space. In some implementations, the imaging sensor **450** is a structured-light 3D scanner that measures the three-dimensional shape of an object using projected light patterns. Projecting a narrow band of light onto a three-dimensionally shaped surface produces a line of illumination that appears distorted from other perspectives than that of the projector, and can be used for an exact geometric reconstruction of the surface shape (light section). The imaging sensor **450** may use laser interference or projection as a method of stripe pattern generation. The laser interference method works with two wide planar laser beam fronts. Their interference results in regular, equidistant line patterns. Different pattern sizes can be obtained by changing the angle between these beams. The method allows for the exact and easy generation of very fine patterns with unlimited depth of field. The projection method uses non coherent light and basically works like a video projector. Patterns are generated by a display within the projector, typically an LCD (liquid crystal) or LCOS (liquid crystal on silicon) display.

**[0088]** In some implementations, the imaging sensor **450** is a still-image camera, a video camera, a stereo camera, or a three-dimensional point cloud imaging sensor configured to capture still images and/or video. The imaging sensor **450** may capture one or more images and/or video of a person **20** identified within the environment **10** of the robot **100**. In some examples, the camera is used for detecting objects and detecting object movement when a position of the object changes in an occupancy map in successive images.

**[0089]** In some implementations, the imaging sensor **450** is a time-of-flight camera (TOF camera), which is a range imaging camera system that resolves distance based on the known speed of light, measuring the time-of-flight of a light signal between the camera and the subject for each point of the image. The time-of-flight camera is a class of scannerless LIDAR, in which the entire scene is captured with each laser or light pulse, as opposed to point-by-point with a laser beam, such as in scanning LIDAR systems.

**[0090]** In some implementations, the imaging sensor **450** is a three-dimensional light detection and ranging sensor (e.g., Flash LIDAR). LIDAR uses ultraviolet, visible, or near infrared light to image objects and can be used with a wide range of targets, including non-metallic objects, rocks, rain, chemical compounds, aerosols, clouds and even single molecules. A narrow laser beam can be used to map physical features with very high resolution. Wavelengths in a range from about 10 micrometers to the UV (ca. 250 nm) can be used to suit the target. Typically light is reflected via backscattering. Different types of scattering are used for different LIDAR applications; most common are Rayleigh scattering, Mie scattering and Raman scattering, as well as fluorescence.

**[0091]** In some implementations, the imaging sensor **450** includes one or more triangulation ranging sensors, such as a position sensitive device. A position sensitive device and/or position sensitive detector (PSD) is an optical position sensor (OPS) that can measure a position of a light spot in one or two-dimensions on a sensor surface. PSDs can be divided into two classes, which work according to different principles. In the first class, the sensors have an isotropic sensor surface that has a raster-like structure that supplies continuous position data. The second class has discrete sensors on the sensor surface that supply local discrete data.

**[0092]** The imaging sensor **450** may employ range imaging for producing a 2D image showing the distance to points in a scene from a specific point, normally associated with some type of sensor device. A stereo camera system can be used for determining the depth to points in the scene, for example, from the center point of the line between their focal points.

**[0093]** The imaging sensor **450** may employ sheet of light triangulation. Illuminating the scene with a sheet of light creates a reflected line as seen from the light source. From any point out of the plane of the sheet, the line will typically appear as a curve, the exact shape of which depends both on the distance between the observer and the light source and the distance between the light source and the reflected points. By observing the reflected sheet of light using the imaging sensor **450** (e.g., as a high resolution camera) and knowing the positions and orientations of both camera and light source, the robot **100** can determine the distances between the reflected points and the light source or camera.

**[0094]** In some implementations, the proximity or presence sensor **410** includes at least one of a sonar sensor, ultrasonic ranging sensor, a radar sensor (e.g., including Doppler radar and/or millimeter-wave radar), or pyrometer. A pyrometer is a non-contacting device that intercepts and measures thermal radiation. Moreover, the presence sensor **410** may sense at least one of acoustics, radiofrequency, visible wavelength light, or invisible wavelength light. The presence sensor **410** may include a non-infrared sensor, for example, to detect obstacles having poor infrared response (e.g., angled, curved and/or specularly reflective surfaces). In some examples, the presence sensor **410** detects a presence of an obstacle within a dead band of the imaging or infrared range sensor **450** substantially immediately adjacent that sensor (e.g., within a range at which the imaging sensor **450** is insensitive (e.g., 1 cm-40 cm; or 5 m-infinity)).

**[0095]** The laser scanner **440** scans an area about the robot **100** and the controller **500**, using signals received from the laser scanner **440**, may create an environment map or object map of the scanned area. The controller **500** may use the object map for navigation, obstacle detection, and obstacle avoidance. Moreover, the controller **500** may use sensory inputs from other sensors of the sensor system **400** for creating an object map and/or for navigation. In some examples, the laser scanner **440** is a scanning LIDAR, which may use a laser that quickly scans an area in one dimension, as a "main" scan line, and a time-of-flight imaging element that uses a phase difference or similar technique to assign a depth to each pixel generated in the line (returning a two dimensional depth line in the plane of scanning) In order to generate a three dimensional map, the LIDAR can perform an "auxiliary" scan in a second direction (for example, by "nodding" the scanner). This mechanical scanning technique can be complemented, if not supplemented, by technologies, such as the "Flash" LIDAR/LADAR and "Swiss Ranger" type focal plane imaging element sensors and techniques, which use semiconductor stacks to permit time of flight calculations for a full 2-D matrix of pixels to provide a depth at each pixel, or even a series of depths at each pixel (with an encoded illuminator or illuminating laser).

**[0096]** In some examples, the robot base application **520** communicates with a wheel motor driver **506*a*** for sending motor commands and receiving encoder data and status from the drive motors **220*a-d***. The robot base application **520** may communicate with a panning motor driver **506*b*** for sending motor commands and receiving encoder data and status from the panning system **330**. The robot base application **520** may communicate with one or more USB drivers **506*c*** for receiving sensor data from the camera **168**, a LIDAR sensor **440** (FIG. **1**A) and/or the 3D imaging sensor(s) **450**. Moreover, the robot base application **520** may communicate with one or more Modbus drivers **506*d*** for receiving six axis linear and angular acceleration data from an internal measurement unit (IMU) **470** and/or range data from the proximity sensors **410**.

**[0097]** The sensor system **400** may include an inertial measurement unit (IMU) **470** in communication with the controller **500** to measure and monitor a moment of inertia of the robot **100** with respect to the overall center of gravity $CG_R$ of the robot **100**. The controller **500** may monitor any deviation in feedback from the IMU **470** from a threshold signal corresponding to normal unencumbered operation. For example, if the robot **100** begins to pitch away from an upright position, it may be "clothes lined" or otherwise impeded, or someone may have suddenly added a heavy payload. In these instances, it may be necessary to take urgent action (including, but not limited to, evasive maneuvers, recalibration, and/or issuing an audio/visual warning) in order to ensure safe operation of the robot **100**.

**[0098]** Since the robot **100** may operate in a human environment **10**, it may interact with humans **20** and operate in spaces designed for humans **20** (and without regard for robot constraints). The robot **100** can limit its drive speeds and accelerations when in a congested, constrained, or highly dynamic environment, such as at a cocktail party or busy hospital. However, the robot **100** may encounter situations where it is safe to drive relatively fast, as in a long empty corridor, but yet be able to decelerate suddenly, for example when something crosses the robots' motion path.

**[0099]** When accelerating from a stop, the controller **500** may take into account a moment of inertia of the robot **100** from its overall center of gravity $CG_R$ to prevent robot tipping. The controller **500** may use a model of its pose, including its current moment of inertia. When payloads are supported, the controller **500** may measure a load impact on the overall center of gravity $CG_R$ and monitor movement of the robot moment of inertia. For example, the torso **130** and/or neck **150** may include strain gauges to measure strain. If this is not possible, the controller **500** may apply a test torque command to the drive wheels **210***a-d* and measure actual linear and angular acceleration of the robot **100** using the IMU **470**, in order to experimentally determine safe limits.

**[0100]** Referring to FIG. **5**, in some implementations, the controller **500** (e.g., a device having one or more computing processors **502** in communication with non-transitory memory **504** capable of storing instructions executable on the computing processor(s) **502**) executes a control system **510**, which includes a behavior system **510***a* and a control arbitration system **510***b* in communication with each other. The control arbitration system **510***b* allows robot applications **520** to be dynamically added and removed from the control system **510**, and facilitates allowing applications **520** to each control the robot **100** without needing to know about any other applications **520**. In other words, the control arbitration system **510***b* provides a simple prioritized control mechanism between applications **520** and resources **540** of the robot **100**. The resources **540** may include the drive system **200**, the sensor system **400**, and/or any payloads or controllable devices in communication with the controller **500**.

**[0101]** The applications **520** can be stored in memory of or communicated to the robot **100**, to run concurrently on (e.g., on a processor) and simultaneously control the robot **100**. The applications **520** may access behaviors **530** of the behavior system **510***a*. The independently deployed applications **520** are combined dynamically at runtime and can share robot resources **540** (e.g., drive system **200**, base **120**, torso **130** (including sensor module **300**), and optionally the interface module **140** (including the neck **150** and/or the head **160**)) of the robot **100**. The robot resources **540** may be a network of functional modules (e.g. actuators, drive systems, and groups thereof) with one or more hardware controllers. A low-level policy is implemented for dynamically sharing the robot resources **540** among the applications **520** at run-time. The policy determines which application **520** has control of the robot resources **540** required by that application **520** (e.g. a priority hierarchy among the applications **520**). Applications **520** can start and stop dynamically and run completely independently of each other. The control system **510** also allows for complex behaviors **530**, which can be combined together to assist each other.

**[0102]** The control arbitration system **510***b* includes one or more application(s) **520** in communication with a control arbiter **550**. The control arbitration system **510***b* may include components that provide an interface to the control arbitration system **510***b* for the applications **520**. Such components may abstract and encapsulate away the complexities of authentication, distributed resource control arbiters, command buffering, coordinate the prioritization of the applications **520** and the like. The control arbiter **550** receives commands from every application **520**, generates a single command based on the applications' priorities, and publishes it for the resources **540**. The control arbiter **550** receives state feedback from the resources **540** and may send the state feedback to the applications **520**. The commands of the control arbiter **550** are specific to each resource **540** to carry out specific actions.

**[0103]** A dynamics model **560** executable on the controller **500** is configured to compute the center for gravity (CG) and moments of inertia of various portions of the robot **100** for assessing a current robot state. The dynamics model **560** may be configured to calculate the center of gravity $CG_R$ of the robot **100**, the center of gravity $CG_B$ of the base **120**, or the center of gravity of other portions of the robot **100**. The dynamics model **560** may also model the shapes, weight, and/or moments of inertia of these components. In some examples, the dynamics model **560** communicates with the IMU **470** or portions of one (e.g., accelerometers and/or gyros) in communication with the controller **500** for calculating the various centers of gravity of the robot **100** and determining how quickly the robot **100** can decelerate and not tip over. The dynamics model **560** can be used by the controller **500**, along with other applications **520** or behaviors **530** to determine operating envelopes of the robot **100** and its components.

**[0104]** In some implementations, a behavior **530** is a plug-in component that provides a hierarchical, state-full evaluation function that couples sensory feedback from multiple sources, such as the sensor system **400**, with a-priori limits and information into evaluation feedback on the allowable actions of the robot **100**. Since the behaviors **530** are pluggable into the application **520** (e.g., residing inside or outside of the application **520**), they can be removed and added without having to modify the application **520** or any other part of the control system **510**. Each behavior **530** is a standalone policy. To make behaviors **530** more powerful, it is possible to attach the output of multiple behaviors **530** together into the input of another so that you can have complex combination functions. The behaviors **530** are intended to implement manageable portions of the total cognizance of the robot **100**.

**[0105]** In the example shown, the behavior system **510***a* includes an obstacle detection/obstacle avoidance (ODOA) behavior **530***a* for determining responsive robot actions based on obstacles perceived by the sensor (e.g., turn away; turn around; stop before the obstacle, etc.). A person follow behavior **530***b* may be configured to cause the drive system **200** to follow a particular person based on sensor signals of the sensor system **400** (providing a local sensory perception). A speed behavior **530***c* (e.g., a behavioral routine executable on a processor) may be configured to adjust the speed setting of the robot **100** and a heading behavior **530***d* may be configured to alter the heading setting of the robot **100**. The speed and heading behaviors **530***c*, **530***d* may be configured to execute concurrently and mutually independently. For example, the speed behavior **530***c* may be configured to poll one of the sensors (e.g., the set(s) of proximity sensors **410**), and the heading behavior **530***d* may be configured to poll another sensor (e.g., a proximity sensor **410**, such as a kinetic bump sensor **411** (FIG. 3A)). An aiming behavior **530***e* may be configured to move the robot **100** or portions thereof to aim one or more imaging sensors **450** toward a target or move the imaging sensor(s) **450** to gain an increased field of view **452** of an area about the robot **100**.

**[0106]** Referring to FIGS. **6**A and **6**B, in some implementations, the robot **100** (via the aiming behavior **530***e* executing on the controller **500** or the sensor system **400**) moves or pans the imaging sensor(s) **450**, **450***a-c* to gain view-ability of the corresponding dead zone(s) **453**. An imaging sensor **450** can be pointed in any direction 360 degrees (+/−180 degrees) by moving its associated imaging axis **455**. In some examples, the robot **100** maneuvers itself on the ground to move the imaging axis **455** and corresponding field of view **452** of each imaging sensor **450** to gain perception of the volume of space once in a dead zone **453**. For example, the robot **100** may pivot in place, holonomically move laterally, move forward or backward, or a combination thereof. In additional examples, if the imaging sensor **450** has a limited field of view **452** and/or detection field **457**, the controller **500** or the sensor system **400** can actuate the imaging sensor **450** in a side-to-side and/or up and down scanning manner to create a relatively wider and/or taller field of view to perform robust ODOA. Panning the imaging sensor **450** (by moving the imaging axis **455**) increases an associated horizontal and/or vertical field of view, which may allow the imaging sensor **450** to view not only all or a portion of its dead zone **453**, but the dead zone **453** of another imaging sensor **450** on the robot **100**.

**[0107]** In some examples, each imaging sensor **450** has an associated actuator moving the imaging sensor **450** in the scanning motion. In additional examples, the imaging sensor **450** includes an associated rotating mirror, prism, variable angle micro-mirror, or MEMS mirror array to increase the field of view **452** and/or detection field **457** of the imaging sensor **450**.

**[0108]** In the example shown in FIG. **6**B, the torso **130** pivots about the Z-axis on the base **120**, allowing the robot **100** to move an imaging sensor **450** disposed on the torso **130** with respect to the forward drive direction F defined by the base **120**. An actuator **138** (such as a rotary actuator) in communication with the controller **500** rotates the torso **130** with respect to the base **120**. The rotating torso **130** moves the imaging sensor **450** in a panning motion about the Z-axis providing up to a 360° field of view **452** about the robot **100**. The robot **100** may pivot the torso **130** in a continuous 360 degrees or +/− an angle ≥180 degrees with respect to the forward drive direction F.

**[0109]** With continued reference to the example shown in FIG. **6**B, the robot **100** may include at least one long range sensor **650** arranged and configured to detect an object **12** relatively far away from the robot **100** (e.g., >3 meters). The long range sensor **650** may be an imaging sensor **450** (e.g., having optics or a zoom lens configured for relatively long range detection). In additional examples, the long range sensor **650** is a camera (e.g., with a zoom lens), a laser range finder, LIDAR, RADAR, etc. Detection of far off objects allows the robot **100** (via the controller **500**) to execute navigational routines to avoid the object, if viewed as an obstacle, or approach the object, if viewed as a destination (e.g., for approaching a person **20** for capturing an image **50** or video of the person **20**). Awareness of objects outside of the field of view of the imaging sensor(s) **450** on the robot **100** allows the controller **500** to avoid movements that may place the detected object **12** in a dead zone **453**. Moreover, in person following routines, when a person **20** moves out of the field of view of an imaging sensor **450**, the long range sensor **650** may detect the person **20** and allow the robot **100** to maneuver to regain perception of the person **20** in the field of view **452** of the imaging sensor **450**. In some implementations, in image or video capturing routines, the robot **100** maneuvers to maintain continuous alignment of the imaging or long-range sensors **450**, **650** on a person **20** such that perception of the person **20** is continuously in the field of view **452** of the imaging or long-range sensors **450**, **650**.

**[0110]** Referring to FIGS. **7**A and **7**B, in some implementations, while patrolling the environment **10**, the robot **100** needs to scan the imaging sensor(s) **450** from side to side and/or up and down to detect a person **20** around an occlusion **16**. In the examples shown, the person **20** and a wall **18** create the occlusion **16** within the field of view **452** of the imaging sensor **450**. Moreover, the field of view **452** of the imaging sensor **450** having a viewing angle θv of less than 360 can be enlarged to 360 degrees by optics, such as omni-directional, fisheye, catadioptric (e.g., parabolic mirror, telecentric lens), panamorph mirrors and lenses.

**[0111]** The controller **500** may use imaging data **50** from the imaging sensor **450** for color/size/dimension blob matching. Identification of discrete objects (e.g., walls **18**, person(s) **20**, furniture, etc.) in a scene **10** about the robot **100** allows the robot **100** to not only avoid collisions, but also to search for people **20**, **20***a-b*. The human interface robot **100** may need to identify target objects and humans **20**, **20***a-b* against the background of the scene **10**. The controller **500** may execute one or more color map blob-finding algorithms on the depth map(s) derived from the imaging data **50** of the imaging sensor **450** as if the maps were simple grayscale maps and search for the same "color" (that is, continuity in depth) to yield continuous portions of the image **50** corresponding to people **20** in the scene **10**. Using color maps to augment the decision of how to segment people **20** would further amplify object matching by allowing segmentation in the color space as well as in the depth space. The controller **500** may first detect objects or people **20** by depth, and then further segment the objects **12** by color. This allows the robot **100** to distinguish between two objects (e.g., wall **18** and person **20**) close to or resting against one another with differing optical qualities.

**[0112]** In implementations where the sensor system **400** includes only one imaging sensor **450** (e.g., camera) for object detection, the imaging sensor **450** may have problems imaging surfaces in the absence of scene texture and may not be able to resolve the scale of the scene. Using or aggregating two or more imaging sensors **450** for object detection can provide a relatively more robust and redundant sensor system **400**. The controller **500** may use detection signals from the imaging sensor **450** and/or other sensors of the sensor system **400** to identify a person **20**, determine a distance of the person **20** from the robot **100**, construct a 3D map of surfaces of the person **20** and/or the scene **10** about the person **20**, and construct or update an occupancy map **700**.

**[0113]** As shown in FIGS. **7**A and **7**B, in some circumstances, the robot **100** receives an occupancy map **700** (e.g., from the security system **1000**) of objects including walls **18**

in a patrolling scene **10** and/or a patrolling area **5**, or the robot controller **500** produces (and may update) the occupancy map **700** based on image data and/or image depth data received from an imaging sensor **450** over time. In addition to localization of the robot **100** in the patrolling scene **10** (e.g., the environment about the robot **100**), the robot **100** may patrol by travelling to other points in a connected space (e.g., the patrolling area **5**) using the sensor system **400**. The robot **100** may include a short range type of imaging sensor **450** (e.g., the first imaging sensor **450***a* of the sensor module **300** (FIG. 3B) aimed downward toward the floor surface **5**) for mapping the scene **10** about the robot **100** and discerning relatively close objects **12** or people **20**. The robot **100** may include a long range type of imaging sensor **450** (e.g., the second imaging sensor **450***b* of the sensor module **300** aimed away from the robot **100** and substantially parallel to the floor surface **5**, shown in FIG. 3B) for mapping a relatively larger area about the robot **100** and discerning a relatively far away person **20**. The robot **100** may include a camera **168** (mounted on the head **160**, as shown in FIGS. 1B and 1F) for mapping a relatively larger area about the robot **100** and discerning a relatively far away person **20**. The robot **100** can use the occupancy map **700** to identify and detect people **20** in the scene **10** as well as occlusions **16** (e.g., wherein objects cannot be confirmed from the current vantage point). For example, the robot **100** may compare the occupancy map **700** against sensor data received from the sensor system **400** to identify an unexpected stationary or moving object **12** in the scene **10** and then identify that object **12** as a person **20**. The robot **100** can register an occlusion **16** or wall **18** in the scene **10** and attempt to circumnavigate the occlusion **16** or wall **18** to verify a location of new person **20**, **20***a-b* or other object in the occlusion **16**. The robot **100** can register the occlusion **16** or person **20** in the scene **10** and attempt to follow and/or capture a clear still image **50** or video of the person **20**. Moreover, using the occupancy map **700**, the robot **100** can determine and track movement of a person **20** in the scene **10**. For example, using the imaging sensor **450**, the controller **500** may detect movement of the person **20** in the scene **10** and continually update the occupancy map **700** with a current location of the identified person **20**.

**[0114]** When the robot **100** detects a moving object **12** (via the sensor system **400**), the robot **100** may send a surveillance report **1010** to the remote security system **1000**, regardless of whether the robot **100** can resolve the object **12** as a person **20** or not. The security system **1000** may execute one or more routines (e.g., image analysis routines) to determine whether the object **12** is a person **20**, a hazard, or something else. Moreover, a user of the security system **1000** may review the surveillance report **1010** to determine the nature of the object **12**. For example, sensed movement could be due to non-human actions, such as a burst water pipe, a criminal mobile robot, or some other moving object of interest.

**[0115]** In some implementations, a second person **20***b* of interest, located behind the wall **18** in the scene **10**, may be initially undetected in an occlusion **16** of the scene **10**. An occlusion **16** can be an area in the scene **10** that is not readily detectable or viewable by the imaging sensor **450**. In the example shown, the sensor system **400** (e.g., or a portion thereof, such as the imaging sensor **450**) of the robot **100** has a field of view **452** with a viewing angle $\theta_V$ (which can be any angle between 0 degrees and 360 degrees) to view the scene **10**. In some examples, the imaging sensor **450** includes omni-directional optics for a 360 degree viewing angle $\theta_V$; while in other examples, the imaging sensor **450**, **450***a*, **450***b* has a viewing angle $\theta_V$ of less than 360 degrees (e.g., between about 45 degrees and 180 degrees). In examples where the viewing angle $\theta_V$ is less than 360 degrees, the imaging sensor **450** (or components thereof) may rotate with respect to the robot body **110** to achieve a viewing angle $\theta_V$ of 360 degrees. The imaging sensor **450** may have a vertical viewing angle $\theta_{V-V}$ the same as or different from a horizontal viewing angle $\theta_{V-H}$. For example, the imaging sensor **450** may have a horizontal field of view $\theta_{v-H}$ of at least 45 degrees and a vertical field of view $\theta_{V-V}$ of at least 40 degrees. In some implementations, the imaging sensor **450** can move with respect to the robot body **110** and/or drive system **200**. Moreover, in order to detect the second person **20***b* and capture a still image **50** and/or video of the second person **20***b*, the robot **100** may move the imaging sensor **450** by driving about the patrolling scene **10** in one or more directions (e.g., by translating and/or rotating on the patrolling surface **5**) to obtain a vantage point that allows detection and perception of the second person **20***b* in the field of view **452** of the imaging sensor **450**. In some implementations, in image or video capturing routines, the robot **100** maneuvers to maintain continuous alignment of the imaging or long-range sensors **450**, **650** such that perception of the person **20** is continuously in the field of view **452**, **652** of the imaging or long-range sensors **450**, **650**. Robot movement or independent movement of the imaging sensor(s) **450**, **650** may resolve monocular difficulties as well.

**[0116]** The controller **500** may assign a confidence level to detected locations or tracked movements of people **20** in the scene **10**. For example, upon producing or updating the occupancy map **700**, the controller **500** may assign a confidence level for each person **20** on the occupancy map **700**. The confidence level can be directly proportional to a probability that the person **20** is actually located in the patrolling area **5** as indicated on the occupancy map **700**. The confidence level may be determined by a number of factors, such as the number and type of sensors used to detect the person **20**. The imaging sensor **450** may provide a different level of confidence, which may be higher than the proximity sensor **410**. Data received from more than one sensor of the sensor system **400** can be aggregated or accumulated for providing a relatively higher level of confidence over any single sensor. In some examples, the controller **500** compares new image depth data with previous image depth data (e.g., the occupancy map **700**) and assigns a confidence level of the current location of the person **20** in the scene **10**. The sensor system **400** can update location confidence levels of each person **20**, **20***a-b* after each imaging cycle of the sensor system **400**. When the controller **500** identifies that the location of a person **20** has changed (e.g., is no longer occupying the corresponding location on the occupancy map **700**), the controller **500** may identify that person **20** as an "active" or "moving" person **20** in the scene **10**.

**[0117]** Odometry is the use of data from the movement of actuators to estimate change in position over time (distance traveled). In some examples, an encoder is disposed on the drive system **200** for measuring wheel revolutions, therefore a distance traveled by the robot **100**. The controller **500** may use odometry in assessing a confidence level for an object or person location. In some implementations, the sensor system **400** includes an odometer and/or an angular rate sensor (e.g., gyroscope or the IMU **470**) for sensing a distance traveled by the robot **100**. A gyroscope is a device for measuring or maintaining orientation based on the principles of conservation of angular momentum. The controller **500** may use odometry and/or gyro signals received from the odometer and/or angular rate sensor, respectively, to determine a location of the robot **100** in a working area **5** and/or on an occupancy map **700**. In some examples, the controller **500** uses dead reckoning. Dead reckoning is the process of estimating a current position based upon a previously determined position, and advancing that position based upon known or estimated speeds over elapsed time, and course. By knowing a robot location in the patrolling area **5** (e.g., via odometry, gyroscope, etc.) as well as a sensed location of one or more people **20** in the patrolling area **5** (via the sensor system **400**), the controller **500** can assess a relatively higher confidence level of a location or movement of a person **20** on the occupancy map **700** and in the working area **5** (versus without the use of odometry or a gyroscope).

**[0118]** Odometry based on wheel motion can be electrically noisy. The controller **500** may receive image data from the imaging sensor **450** of the environment or scene **10** about the robot **100** for computing robot motion, through visual odometry. Visual odometry may entail using optical flow to determine the motion of the imaging sensor **450**. The controller **500** can use the calculated motion based on imaging data of the imaging sensor **450** for correcting any errors in the wheel based odometry, thus allowing for improved mapping and motion control. Visual odometry may have limitations with low-texture or low-light scenes **10** if the imaging sensor **450** cannot track features within the captured image(s).

**[0119]** Other details and features on odometry and imaging systems, which may be combinable with those described herein, can be found in U.S. Pat. No. 7,158,317 (describing a "depth-of field" imaging system), and U.S. Pat. No. 7,115,849 (describing wavefront coding interference contrast imaging systems), the contents of which are hereby incorporated by reference in their entireties.

**[0120]** Referring to FIGS. **5** and **7**B, in some implementations, the behavior system **510***a* includes a person follow behavior **530***b*. While executing this behavior **530***b*, the robot **100** may detect, track, and follow a person **20**. The person follow behavior **530***b* allows the robot **100** to observe or monitor the person **20**, for example, by capturing images **50** (e.g., still images **50** and/or video) of the person **20** using the imaging sensor(s) **450**. Additionally, the controller **500** may execute the person follow behavior **530***b* to maintain a continuous perception of the person **20** within the field of view **452** of the imaging sensor **450** to obtain a human recognizable/clear image and/or video, which can be used to identify the person **20** and actions of the person **20**. The behavior **530***b* may cause the controller **500** to aim one or more imaging sensors **168**, **450**, **450***a-c* at the perceived person **20**. The controller **500** may use image data from the third imaging sensor **450***c* of the sensor module **300**, which is arranged to have its imaging axis **455***c* arranged to aim upward and away from the torso **130**, to identify people **20**. The third imaging sensor **450***c* can be arranged to capture images of the face of an identified person **20**. In implementations where the robot **100** has an articulated head **160** with a camera **168** and/or other imaging sensor **450** on the head **160**, as shown in FIG. 2G, the robot **100** may aim the camera **168** and/or other imaging sensor **450** via the neck **150** and head **160** to capture images **50** of an identified person **20** (e.g., images **50** of the face of the person **20**). The robot **100** may maintain the field of view **452** of the imaging sensor **168**, **450** on the followed person **20**. Moreover, the drive system **200** can provide omni-directional and/or holonomic motion to control the robot **100** about planar, forward/back, and rotational directions x, y, and θz, respectively, to orient the imaging sensor **168**, **450** to maintain the corresponding field of view **452** on the person **20**. The robot **100** can drive toward the person **20** to keep the person **20** within a threshold distance range $D_R$ (e.g., corresponding to a sensor field of view **452**). In some examples, the robot **100** turns to face forward toward the person **20** while tracking the person **20**. The robot **100** may use velocity commands and/or waypoint commands to follow the person **20**. In some examples, the robot **100** orients the imaging sensor **168**, **450** to capture a still image and/or video of the person **20**.

**[0121]** Referring to FIG. **8**A, a naïve implementation of person following would result in the robot **100** losing the location of a person **20** once the person **20** has left the field of view **452** of the imaging sensor **450**. One example of this is when the person **20** goes around a corner. To work around this problem, the robot **100** retains knowledge of the last known location of the person **20**, determines which direction the person **20** is heading and estimates the trajectory of the person **20**. The robot **100** may move toward the person **20** to determine the direction of movement and rate of movement of the person **20** with respect to the robot **100**, using the visual data of the imaging sensor(s) **450**. The robot **100** can navigate to a location around the corner toward the person **20** by using a waypoint (or set of waypoints), coordinates, an imaged target of the imaging sensor **450**, an estimated distance, dead reckoning, or any other suitable method of navigation. Moreover, as the robot **100** detects the person **20** moving around the corner, the robot **100** can drive (e.g., in a holonomic manner) and/or move the imaging sensor **450** (e.g., by panning and/or tilting the imaging sensor **450** or a portion of the robot body **110** supporting the imaging sensor **450**) to orient the field of view **452** of the imaging sensor **450** to regain viewing of the person **20**, for example, to capture images **50** of the person **20** and/or observe or monitor the person **20**.

**[0122]** Referring to FIGS. **8**A and **8**B, using the image data received from the image sensor(s) **450**, the control system **510** can identify the person **20**, **20***a* (e.g., by noticing a moving object and assuming the moving object is the person **20**, **20***a* when the object meets a particular height range, or via pattern or image recognition), so as to continue following that person **20**. If the robot **100** encounters another person **20***b*, as the first person **20***a* turns around a corner, for example, the robot **100** can discern that the second person **20***b* is not the first person **20***a* and continues following the first person **20***a*. In some implementations, to detect a person **20** and/or to discern between two people **20**, the image sensor **450** provides image data and/or 3-D image data **802** (e.g., a 2-d array of pixels, each pixel containing depth information) to a segmentor **804** for segmentation into objects or blobs **806**. For example, the pixels are grouped into larger objects based on their proximity to neighboring pixels. Each of these objects (or blobs) is then received by a size filter **808** for further analysis. The size filter **808** processes the objects or blobs **806** into right sized objects or blobs **810**, for example, by rejecting objects that are too small (e.g., less than about 3 feet in height) or too large to be a person **20** (e.g., greater than about 8 feet in height). A shape filter **812** receives the right sized objects or blobs **810** and eliminates objects that do not satisfy a specific shape. The shape filter **812** may look at an expected width of where a midpoint of a head is expected to be using the angle-of-view of the camera **450** and the known distance to the object. The shape filter **812** processes are renders the right sized objects or blobs **810** into person data **814** (e.g., images or data representative thereof). The control system **510** may use the person data **814** as a unique identifier to discern between two people **20** detected near each other, as discussed below.

**[0123]** In some examples, the robot **100** can detect and track multiple persons **20**, **20***a-b* by maintaining a unique identifier for each person **20**, **20***a-b* detected. The person follow behavior **530***b* propagates trajectories of each person **20** individually, which allows the robot **100** to maintain knowledge of which person(s) **20** the robot **100** should track, even in the event of temporary occlusions **16** caused by other persons **20** or objects **12**, **18**.

**[0124]** Referring to FIG. **8**C, in some implementations, a multi-target tracker **820** (e.g., a routine executable on a computing processor, such as the controller **500**) receives the person(s) data **814** (e.g., images or data representative thereof) from the shape filter **812**, gyroscopic data **816** (e.g., from the IMU **470**), and odometry data **818** (e.g., from the drive system **200**) provides person location/velocity data **822**, which is received by the person follow behavior **530***b*. In some implementations, the multi-target tracker **820** uses a Kalman filter to track and propagate each person's movement trajectory, allowing the robot **100** to perform tracking beyond a time when a user is seen, such as when a person **20** moves around a corner or another person **20** temporarily blocks a direct view to the person **20**.

**[0125]** Referring to FIG. **8**D, in some examples, the person follow behavior **530***b* causes the controller **500** to move in a manner that allows the robot **100** to capture a clear picture of a followed person **20**. For example, the robot **100** may: (1) maintain a constant following distance $D_R$ between the robot **100** and the person **20** while driving; (2) catch up to a followed person **20** (e.g., to be within a following distance $D_R$ that allows the robot **100** to capture a clear picture of the person **20** using the imaging sensor **450**); (3) speed past the person **20** and then slow down to capture a clear picture of the person **20** using the imaging sensor **450**.

**[0126]** The person follow behavior **530***b* can be divided into two subcomponents, a drive component **830** and an aiming component **840**. The drive component **830** (e.g., a follow distance routine executable on a computing processor) may receive the person data **814**, person velocity data **822**, and location data **824** (e.g., waypoints, coordinates, headings, distances to objects, etc. of the robot **100**) to determine (e.g., via the computing processor) the following distance $D_R$ (which may be a range). The drive component **830** controls how the robot **100** may try to achieve its goal, depending on the distance to the person **20**. If the robot **100** is within a threshold distance, velocity commands are used directly, allowing the robot **100** to maintain the following distance $D_R$ or some other distance that allows the robot **100** to capture a clear picture of the person **20** using the imaging sensor **450**. If the person **20** is further than the desired distance, the controller **500** may use the location data **824** to move closer to the person **20**. The drive component **830** may further control holonomic motion of the robot **100** to maintain the field of view **452** of the image sensor **450** (e.g., of the sensor module **300** and/or the head **160**), on the person **20** and/or to maintain focus on the person **20** as the robot **100** advances toward or follows the person **20**.

**[0127]** The aiming component **840** causes the controller **500** to move the imaging sensor **450** or a portion of the robot body **110** supporting the imaging sensor **450** to maintain the field of view **452** of the image sensor **450** on the person **20**. In examples where the robot **100** includes an interface module **140**, the controller **500** may actuate the neck **150** to aim the camera **168** or the imaging sensor on the head **160** toward the person **20**. In additional examples, the controller **500** may rotate the sensor module **300** on the torso **130** to aim one of the imaging sensors **450***a-c* of the sensor module **300** toward the person **20**. The aiming routine **840** (e.g., executable on a computing processor) may receive the person data **814**, the gyroscopic data **816**, and kinematics **826** (e.g., from the dynamics model **560** of the control system **510**) and determine a pan angle **842** and/or a tilt angle **844**, as applicable to the robot **100** that may orient the image sensor **450** to maintain its field of view **452** on the person **20**. There may be a delay in the motion of the base **120** relative to the pan-tilt of the head **160** and also a delay in sensor information arriving to the person follow behavior **530***b*. This may be compensated for based on the gyro and odometry information **816**, **818** so that the pan angle $\theta_R$ does not overshoot significantly once the robot **100** is turning.

**[0128]** Referring to FIG. **8**E, in some examples, the controller **500** uses the behavior system **510***a* to execute the aiming behavior **530***e* to aim the corresponding field of view **452**, **652** of at least one imaging sensor **450**, **650** to continuously perceive a person **20** within the field of view **452**, **652**. In some examples, the aiming behavior **530***e* (via the controller **500**) aims the field of view **452**, **652** to perceive a facial region of the person **20**. In some examples, a person **20** is moving while the image sensor(s) **450**, **650** capture images **50**. Due to the movement by the person **20**, in addition to the focal range and shutter speed of the imaging sensor **450**, **650** and dynamics of the robot **100** (e.g., velocity/holonomic motion), the person **20** may not be centered in the captured image **50** or the image **50** may be blurred. If the person **20** is not centered in the captured image **50** and/or the image **50** is blurred, the person **20** may not be recognizable. Accordingly, the aiming behavior **530***e* factors in a movement trajectory TR (e.g., as shown in FIG. **14**B) of the person **20** and the planar velocity of the robot **100**. Using the movement trajectory TR and/or the planar velocity of the robot **100**, the controller **500** may command movement of the robot **100** (via the drive system **200**) and/or movement of a portion of the robot body **110** (e.g., torso **130**, sensor module **300**, and/or interface module **140**) to aim of the imaging sensor **450**, **650** to maintain the corresponding field of view **452**, **652** on the identified person **20**. In some examples, the command is a drive command at a velocity proportional to the movement trajectory TR of the identified person **20**. In examples where the robot **100** includes the interface module **140**, the command may include a pan/tilt command of the neck **150** at a velocity proportional to a relative velocity between the person **20** and the robot **100**. The controller **500** may additionally or alternatively command (e.g., issue drive commands to the drive system **200**) the robot **100** to move in a planar direction with three degrees of freedom (e.g., holonomic motion) while maintaining the aimed field of view **452**, **652** of the imaging sensor **450**, **650** on the identified person **20** associated with the movement trajectory. The robot **100** knows its limitations (e.g., how fast the robot **100** can decelerate from a range of travel speeds) and can calculate how quickly the drive system **200** needs to advance and then decelerate/stop to capture one or more images **50** with the image sensor(s) **450** mounted on the robot **100**. Moreover, the robot **100** may pace the moving object **12** (e.g., the person **20**) to get a rear or sideways image of the moving object **12**.

**[0129]** The aiming behavior **530***e*, for aiming the image sensor(s) **450**, **650**, can be divided into two subcomponents, a dive component **830** and an aiming component **840**. The dive component **830** (a speed/heading routine executable on a computing processor) may receive the person data **814** (FIG. **8**B), person tracking (e.g., trajectory) data **820** (FIG. **8**B), person velocity data **822** (FIG. **8**C), and location data **824** (FIG. **8**C) to determine drive commands (e.g., holonomic motion commands) for the robot **100**. For example, the controller **500** may command the robot **100** to move in a planar direction of the three planar velocities (forward/back, lateral, and rotational) x, y, and θz, respectively, for aiming the field of view **452**, **652** of the image device **450**, **650** to continuously perceive the person **20** in the field of view **452**, **652**. The person **20** may be in motion or stationary. In some examples, the drive routine **830** can issue drive commands to the drive system **200**, causing the robot **100** to drive away from the person **20** once an acceptable image and/or video is captured. In other examples, the robot **100** continues following the person **20**, using the person follow behavior **530***b*, and sends one or more surveillance reports **1010** (e.g., time stamped transmissions with trajectory calculations) to the security system **1000** until the person **20** is no longer trackable. For example, if the person **20** goes through a stairwell door, the robot **100** may send a surveillance report **1010** to the security system **1000** that includes a final trajectory prediction TR of the person **20** and/or may signal stationary stairwell cameras or robots on other adjacent floors to head toward the stairwell to continue tracking the moving person **20**.

**[0130]** The aiming component **840** causes movement of the robot **100** (via the drive system **200**) and/or portions of the robot **100** (e.g., rotate the sensor module **300**, pan and/or tilt the neck **150**) to aim the field of view **452**, **652** of the image device **450**, **650** to continuously perceive the person **20** in the field of view **452**, **652**. In some examples, the aiming component **840** aims the field of view **452**, **652** independent of the drive component **830**. For example, the controller **500** may decide to only utilize the aiming component **840** to aim the field of view **452**, **652**. In other examples, the controller **500** utilizes both the aiming component **840** and the drive component **830** to aim the field of views **452**, **652** on the person **20**. The aiming component **840** (e.g., executable on a computing processor) may receive the person data **814** (FIG. **8**B), the person tracking (e.g., trajectory) data **820** (FIG. **8**B), the gyroscopic data **816** (FIG. **8**C), kinematics **826** (e.g., from the dynamics model **560** of the control system **510**), and shutter speed data **832** (e.g., from the imaging sensor(s) **450**, **650**) and determine an appropriate movement command for the robot **100**. In examples where the robot **100** includes the interface module **140**, the movement command may include a pan angle **842** and/or a tilt angle **844** that may translate the imaging sensor **450**, **650** to maintain its field of view **452**, **652** to continuously perceive the person **20**. The aiming component **840** may determine a velocity at which the pan angle **842** and the tilt angle **844** translate proportional to the movement trajectory TR of the person **20** so that the field of view **452**, **652** does not undershoot or overshoot a moving person **20**, thereby safeguarding the person is centered in an image (or video) captured by the at least one imaging sensor **450**, **650**. There may be a delay in the motion of the base **120** relative to the pan-tilt of the head **160** and also a delay in sensor information arriving to the behavior system **510***a*. This may be compensated for based on the gyro and odometry information **816**, **818** so that the pan angle $\theta_R$ does not overshoot significantly once the robot is turning.

**[0131]** Referring to FIG. **9**A, in some examples, the person follow behavior **530***b* causes the robot **100** to navigate around obstacles **902** to continue following the person **20**. The person follow behavior **530***b* may consider a robot velocity and robot trajectory in conjunction with a person velocity and a person direction of travel, or heading, to predict a future person velocity and a future person trajectory on a map of the environment, such as the occupancy map **700** (either a pre-loaded map stored in the robot memory or stored in a remote storage database accessible by the robot over a network, or a dynamically built map established by the robot **100** during a mission using simultaneous localization and mapping (SLAM)). The robot **100** may also use an ODOA (obstacle detection/obstacle avoidance) behavior **530***a* to determine a path around obstacles **902**, while following the person **20**, for example, even if the person **20** steps over obstacles **902** that the robot **100** cannot traverse. The ODOA behavior **530***a* (FIG. **5**) can evaluate predicted robot paths (e.g., a positive evaluation for predicted robot path having no collisions with detected objects). The control arbitration system **510***b* can use the evaluations to determine the preferred outcome and a corresponding robot command (e.g., drive commands).

**[0132]** Referring to FIGS. **9**A and **9**B, in some implementations, the control system **510** builds a local map **900** of obstacles **902** in an area near the robot **100**. The robot **100** distinguishes between a real obstacle **902** and a person **20** to be followed, thereby enabling the robot **100** to travel in the direction of the person **20**. A person-tracking algorithm can continuously report to the ODOA behavior **530***a* a location of the person **20** being followed. Accordingly, the ODOA behavior **530***a* can then update the local map **900** to remove the obstacle **902** previously corresponding to the person **20** and can optionally provide the current location of the person **20**.

**[0133]** Referring to FIGS. **10**A and **10**B, in some implementations, the robot **100** monitors a patrolling environment **10** of a facility for unauthorized persons **20**. In some examples, the security system **1000** or some other source provides the patrolling robot **100** with a map **700** (e.g., an occupancy or layout map) of the patrolling environment **10** for autonomous navigation. In other examples, the robot **100** builds a local map **900** using SLAM and sensors of the sensor system **400**, such as the camera **168**, the imaging sensors **450**, **450***a-c*, infrared proximity sensors **410**, laser scanner **440**, IMU **470**, sonar sensors, drive motors **220***a-d*, the panning motor **330**, as described above in reference to the robot base **120** sensor module **300**, and/or the head **160**. For example, in a facility, such as an office building, the robot **100** may need to know the location of each room, entrances and hallways. The layout map **700** may include fixed obstacles **18**, such as walls, hallways, and/or fixtures and furniture. In some implementations, the robot **100** receives the layout map **700** and can be trained to learn the layout map **700** for autonomous navigation.

**[0134]** The controller **500** may schedule patrolling routines for the robot **100** to maneuver between specific locations or control points on the layout map **700**. For example, while patrolling around the building, the robot **100** may record its position at specific locations on the layout map **700** at predetermined time intervals set forth by the patrolling routine schedule. While patrolling the environment **10**, the robot **100** may capture image data (e.g., still images and/or video, 2D or 3D) along the field of view **452** of the imaging sensor(s) **450**, at one or more specific locations set forth by the patrolling routine schedule. The robot **100** (via the controller **500**) may tag the image data (e.g., tag each image and/or video) obtained with the corresponding location and time. The robot **100** may send a surveillance report **1010**, such as that in FIG. 1B that includes the tagged images and/or video obtained during the patrolling routine to the security system **1000** upon completing the patrolling routine or instantaneously after obtaining each image **50** and/or video. For example, the robot **100** may communicate wirelessly over a network **102** to send emails, text messages, SMS messages and/or voice messages that include the time stamp data included in the message **1012**, photographs **50**, person trajectory TR, and/or location maps **700** included in the surveillance reports **1010** to the security system **1000** or a remote user, such as a smartphone device of a business owner whose business property is being patrolled by the robot **100**.

**[0135]** In response to detecting a change in the environment **10** about the robot **100** using the sensor system **400** (e.g., detecting movement, noise, lighting changes, temperature changes, etc.), the robot **100** may deviate from a patrolling routine to investigate the detected change. For example, in response to the sensor module **300** detecting movement in the environment **10** about the robot **100** using one or more of the imaging sensors **450**, **450***a-c*, the controller **500** may resolve a location on the layout map **700** of the sensed movement based on three-dimensional volumetric point cloud data of the imaging sensor(s) **450**, **450***a-c* and command the drive system **200** to move towards that location to investigate a source of the movement. In some examples, the sensor module **300** rotates or scans about its collar axis C to identify environment changes; while in other examples, the sensor module **300** rotates or scans about its collar axis C after identification on an environment change, to further identify a source of the environment change.

**[0136]** The robot **100** may detect motion of an object by comparing a position of the object in relation to an occupancy map **700** (FIG. **7**A) in successive images **50**. Similarly, the robot **100** may detect motion of an object by determining that the object becomes occluded in subsequent images **50**. In some examples, the robot **100** propagates a movement trajectory (FIG. **10**C) using a Kalman filter. When object motion is detected, the control system **510** of the robot **100** may be prompted to determine whether or not the detected object in motion is a person **20** using the image data **50** received from the imaging sensor(s) **450**. For example, as shown in FIG. **10**B, the control system **510** may identify the person **20** based on the received image **50** and/or 3-D data and process person data **814** associated with the person **20**.

**[0137]** In some implementations, the robot **100** uses at least one imaging sensor **168**, **450** to capture a human recognizable still image and/or video of a person **20** based on the processed person data **814** associated with the person **20**. For example, the controller **500** may command the robot **100** to maneuver holonomically and/or command rotation/pan/tilt of the neck **150** and head **160** of the robot **100** to aim the field of the view **452** of the imaging sensor **450** to perceive a facial region of the person **20** within the field of view **452** and snap a crisp photo for transmission to a remote recipient.

**[0138]** In additional implementations, sensors **410**, **440**, **450** positioned on the robot **100** at heights between 3-5 feet may simultaneously detect movement and determine that the object **12** extending between these ranges is a person **20**. In still more implementations, the robot **100** may assume that a moving object **12** is a person **20**, based on an average speed of a walking/running person (e.g., between about 0.5 mph and 12 mph).

**[0139]** The robot **100** may capture another image of the person **20** if a review routine executing on the control system **510** determines the person **20** is not recognizable (e.g., the person **20** is not centered in the image **50** or the image **50** is blurred). The controller **500** may tag a location and/or a time associated with the human recognizable image **50** of the person **20** and transmit the captured image **50** and associated location/time tags in the surveillance report **1010** to the security system **1000**. In some implementations, the robot **100** chooses to track and/or follow the person **20** (FIG. **10**B).

**[0140]** In order to investigate actions of a person **20**, the controller **500** may execute one or more behaviors **530** to gain a vantage point of the person **20** sufficient to capture images **50** using the imaging sensor(s) **450** and/or other sensor data from other sensors of the sensor system **400**. In some examples, the controller **500** tracks the person **20** by executing the person follow behavior **530***b* to propagate a movement trajectory TR of the person **20**. As discussed above, the multi-target tracker **820** (FIG. **8**C) may receive the person data **814** from the shape filter **812**, gyroscopic data **816** (e.g., from the IMU **470**), and odometry data **818** (e.g., from the drive system **200**) to provide person location/velocity data **822**, which is received by the person follow behavior **530***b*. The person follow behavior **530***b* may determine the movement trajectory TR of the person **20** once, periodically, continuously, or as the person follow behavior **530***b* determines that the followed person **20** has moved outside of the observed volume of space S. For example, when the followed person **20** moves outside of the observed volume of space S (e.g., around a corner), the person follow behavior **530***b* may determine the movement trajectory TR of the person **20**, so as to move toward and continue to follow the person **20** from a vantage point that allows the robot **100** to capture images **50** of the person **20** using the imaging sensor(s) **450**. The controller **500** may use the movement trajectory TR of the person **20** to move in a direction that the robot **100** perceived the person **20** was traveling when last detected by the sensor system **400**.

**[0141]** Additionally, the robot **100** may employ the person follow behavior **530***b* to maintain a following distance $D_R$ between the robot **100** and the person **20** while maneuvering across the floor surface **5** of the patrolling environment **10**. The robot **100** may need to maintain the following distance $D_R$ in order to capture a video of the person **20** carrying out some action without alerting the person **20** of the presence of the robot **100**. As discussed above, the drive component **830** (FIG. **8**D) may receive the person data **814**, velocity data **822**, and location data **824** to maintain the following distance $D_R$ and control holonomic motion of the robot **100** to maintain the aimed field of view **452** of the image sensor **450** on the person **20**. Additionally, the aiming component **840** (FIG. **8**D) may receive the person data **814**, the gyroscopic data **816**, and kinematics **826** and determine a pan angle **842** and a tilt angle **844** that may maintain the aimed field of view **452** on the person **20**. In some examples, the controller **500** navigates the robot **100** toward the person **20** based upon the trajectory TR propagated by the person follow behavior **530***b*. The controller **500** may accommodate for limitations of the imaging sensor **450** by maneuvering the robot **100** based on the trajectory TR of the person **20** to capture image data **50** (e.g., still images or video) of the person **20** along a field of view **452** of the imaging sensor **450**. The controller **500** may account for dynamics of the person **20** (e.g., location, heading, trajectory, velocity, etc.), shutter speed of the imaging sensor **450** and dynamics of the robot **100** (e.g., velocity/holonomic motion) to aim the corresponding field of view **452** of the imaging sensor **450** to continuously perceive the person **20** within the field of view **452**, so that the person **20** is centered in the captured image **50** and the image **50** is clear. Moreover, the controller **500** may execute movement commands to maneuver the robot **100** in relation to the location of the person **20** to capture a crisp image **50** of a facial region of the person **20**, so that the person **20** is recognizable in the image **50**.

**[0142]** The controller **500** may use the trajectory prediction TR of the person **20** to place the imaging sensor **450** (e.g., via drive commands and/or movement commands of the robot body **110**) where the person **20** may be in the future, so that the robot **100** can be stationary at location ready to capture an image **50** of the person **20**, as the person **20** passes by the robot **100**. For example, when the person **20** is quickly passing close to the robot **100**, the robot **100** may rotate, move, and stop ahead of the person **20** along the predicted trajectory TR of the person **20** to be nearly still when the person **20** enters the field of view **452** of the imaging sensor **450**. Moreover, the controller **500** may use the predicted trajectory TR of the person **20** to track a person **20** headed down a corridor and then, where possible, maneuver along a shorter path using the layout map **700** to arrive at a location along the predicted trajectory TR ahead of the person **20** to be nearly still when the person **20** enters the field of view **452** of the imaging sensor **450**.

**[0143]** In some examples, the controller **500** accommodates for limitations of the drive system **200**. For example, the drive system **200** may have higher deceleration limits for a stop command than a slow-down command. Moreover, the controller **500** may accommodate for any latency between sending an image capture request to the imaging sensor **450** and the actual image capture by the imaging sensor **450**. By knowing the declaration limits of the drive system **200** and an image capture latency of the imaging sensor **450**, the controller **500** can coordinate movement commands (e.g., to move and stop) with image capture commands to the imaging sensor **450** to capture clear, recognizable images **50** of a person **20**.

**[0144]** In some implementations, the drive system **200** has a normal acceleration/deceleration limit of 13.33 radians/sec for each wheel **210***a-d* and a stop deceleration limit of 33.33 radians/sec for each wheel **210***a-d*. Moreover, the imaging sensor **450** may have a horizontal field of view $\theta_{V-H}$ of 50 degrees and a vertical field of view $\theta_{V-V}$ of 29 degrees. For this scenario, the controller **500** may command the drive system **200** and/or portions of the robot body **110** to move the imaging sensor **450** so that a moving object **12**, projected 0.25 seconds in the future (based on a predicted trajectory TR of the object **12** and a speed estimate), is within 21 degrees of the imaging sensor **450** and a current rotational velocity of the robot **100** (as measured by the IMU **470**) is less than 15 degrees per second. A linear velocity of the robot **100** may not have as high of an impact on image blur as rotational velocity. When the object **12** is not in frame, the controller **500** may project the object trajectory TR two seconds into the future and command the drive system **200** to move to a location in one second (adjusting at 10 Hz). If the sign of the current rotational velocity of the robot **100** is opposite of a commanded rotational velocity, the controller **500** may issue a stop command (e.g., zero velocity command) first to use the higher acceleration/deceleration limit associated with the stop command, and then start commanding a desired speed when the robot **100** approaches a velocity close to zero. Similarly, if a linear velocity of the robot **100** is >0.2 m/s, the controller **500** may issue the stop command before issuing the rotational command to the drive system **200**.

**[0145]** In examples where the imaging sensor **450** provides three-dimensional volumetric point cloud data, the controller **500** may use the three-dimensional volumetric point cloud data to determine a distance of the person **20** from the robot **100** and/or a movement trajectory TR of the person **20** and then adjust a position or movement of the robot **100** with respect to the person **20** (e.g., by commanding the drive system **200**) to bring the person **20** within a focal range of the imaging sensor **450** or another imaging sensor **450***a-c* on the robot **100** and/or to bring the person **20** into focus.

**[0146]** In some examples, the controller **500** accounts for lighting in the scene **10**. If the robot **100** is not equipped with a good light source for dark locations in the scene **10** or if the robot **100** is in a highly reflective location of the scene, where a light source may saturate the image **50**, the controller **500** may perceive that the images **50** are washed out or too dark and continue tracking the person **20** until the lighting conditions improve and the robot **100** can capture clear recognizable images **50** of the person **20**.

**[0147]** The controller **500** may consider the robot dynamics (e.g., via the sensor system **400**), person dynamics (e.g., as observed by the sensor system **400** and/or propagated by a behavior **530**), and limitations of the imaging sensor(s) **450** (e.g., shutter speed, focal length, etc.) to predict movement of the person **20**. By predicting movement of the person **20** and maneuvering based on the predicted movement, the robot **100** may capture clear/recognizable images **50** of the person **20**. Moreover, the robot **100** can send a surveillance report **1010** (FIG. **1**B) to the security system **1000** (or some other remote recipient) that contains a message **1012** and/or attachments **1014** that are useful for surveillance of the environment **10**. The message **1012** may include a date-timestamp, location of the robot **100**, information relating to dynamics of the robot **100**, and/or information relating to dynamics of the person **20** (e.g., location, heading, trajectory, etc.). The attachments **1014** may include images **50** from the imaging sensor(s) **450**, the layout map **700**, and/or other information. In some examples, the surveillance report **1010** includes a trajectory prediction TR of the person **20** (or other object) drawn schematically on the map **700**. The images **50** may correspond to the observed moving object **12** (e.g., the person **20**) and/or the environment **10** about the robot **100**. The surveillance report **1010** enables a remote user to make a determination whether there is an alarm condition or a condition requiring no alarm (e.g. a curtain blowing in the wind).

**[0148]** FIG. **11** provides an exemplary arrangement of operations, executable on the controller **500**, for a method **1100** of operating the robot **100** when a moving object **12** or a person **20** is detected while maneuvering the robot **100** in a patrol environment **10** using a layout map **700**. The layout map **700** can be provided by the security system **1000** or another source. With additional reference to FIGS. **10**A and **10**B, at operation **1102**, the method **1100** includes maneuvering the robot **100** in the patrolling environment **10** according to a patrol routine. The patrol routine may be a scheduled patrol routine including autonomous navigation paths between specific locations or control points on the layout map **700**. At operation **1104**, the method **1100** includes receiving images **50** of the patrolling environment **10** about the robot **100** (via the imaging sensor(s) **450**). At operation **1106**, the method **1100** includes identifying an object **12** in the patrolling environment **10** based on the received images **50**, and at operation **1108**, determining if the object **12** is a person **20**. If the object **12** is not a person **20**, the method **1100** may resume with maneuvering the robot **100** in the patrolling environment **10** according to a patrol routine, at operation **1102**. If the object **12** is a person **20**, the method **1100** includes executing a dynamic image capture routine **1110** to capture clear images **50** of the person **20**, which may be moving with respect to the robot **100**. The dynamic image capture routine **1110** may include executing one or more of person tracking **1112**, person following **1114**, aiming **1116** of image sensor(s) **450** or image capturing **1118**, so that the robot **100** can track the person, control its velocity, aim its imaging sensor(s) and capture clear images **50** of the person **20**, while the person **20** and/or the robot **100** are moving with respect to each other.

**[0149]** The controller **500** may execute person tracking **1112**, for example, by employing the multi-target tracker **820** (FIG. **8**C) to track a trajectory TR of the person **20** (e.g., by using a Kalman filter). In some implementations, the controller **500** commands the robot **100** (e.g., by issuing drive commands to the drive system **200**) to move in a planar direction with three planar degrees of freedom while maintaining the aimed field of view **452**, **652** of the at least one imaging sensor **450**, **650** on the identified person **20** associated with the movement trajectory TR. In some examples, the drive system **200** moves the robot **100** in the planar direction at a velocity proportional to the movement trajectory (e.g., person velocity **822**). In some implementations, the controller **500** commands the robot **100** (e.g., aiming component **840**) to aim the at least one imaging sensor **450**, **650** to maintain the aimed field of view **452**, **652** on the identified person **20** associated with the movement trajectory TR (e.g., via the rotator **152** and/or the tilter **154**, or the sensor module **300**). In some examples, the aiming component **840** moves the imaging sensor **450**, **650** at a velocity proportional to the movement trajectory TR of the identified person **20**. Additionally, the velocity of aiming movement may be further proportional to a planar velocity of the robot **100** and may take into consideration limitations including focal range and shutter speed of the imaging sensor **450**.

**[0150]** The controller **500** may execute the person following **1114** (e.g., employing the drive component **830** and/or the aiming component **840** (FIG. **8**D)) to maintain a following distance $D_R$ on the person **20**. The controller **500** may execute the aiming **1116** of imaging sensor(s) **450** (e.g., employing the aiming component **840** (FIG. **8**E)) to determine an appropriate pan angle **842** and/or tilt angle **844** that may translate the imaging sensor(s) **450**, **650** to maintain its field of view **452**, **652** to continuously perceive the person **20**. The controller **500** executes image capturing **1118** to capture a clear, human recognizable still image and/or video of the person **20**, while considering limitations of the imaging sensor **450**, such as shutter speed and focal range, for example. When the controller **500** commands the at least one imaging sensor **450**, **650** to capture a human recognizable image (or video), the controller **500** may execute one or more components of the person following behavior **530***b* to maintain the aimed field of view **452**, **652** of the imaging sensor **450**, **650** on the identified person **20**. For example, the controller **500** may command the robot to move holonomically and/or command the aiming component **840** to maintain the aimed field of view **452**, **652** to continuously perceive the person **20** in the field of view **452**, **652** of the one or more imaging sensors **450**, **650** (e.g., of the sensor module **300**, the interface module **140**, or elsewhere on the robot **100**).

**[0151]** The method **1100** may include, at operation **1120**, sending a surveillance report **1010** to the security system **1000** or some other remote recipient. As discussed above, the surveillance repot **1010** may include information regarding the dynamic state of the robot **100** (e.g., location, heading, trajectory, etc.), the dynamic state of the observed object **12** or person **20** (e.g., location, heading, trajectory, etc.), and/or images **50** captured of the observed object **12** or person **20**.

**[0152]** FIG. **12**A provides an exemplary arrangement of operations, executable on the controller **500**, for a method **1200** of operating the robot **100** to patrol an environment **10** using a layout map **700**. FIG. **12**B illustrates an example layout map **700** of an example patrol environment **10**. The method **1200** includes, at operation **1202**, receiving the layout map **700** (e.g., at the controller **500** of the robot **100** from a security system **1000** or a remote source) corresponding to the patrolling environment **10** for autonomous navigation during a patrolling routine. For example, the patrolling routine may provide specific locations L, $L_{1-n}$ (FIG. **12**B) or control points on the layout map **700** for autonomous navigation by the robot **100**. The security system **1000** may provide the layout map **700** to the robot **100** or the robot **100** may learn the layout map **700** using the sensor system **400**. The patrolling routine may further assign predetermined time intervals for patrolling the specific locations L on the layout map **700**. At operation **1204**, the method **1200** includes maneuvering the robot **100** in the patrolling environment **10** according to the patrol routine, and at operation **1206**, capturing images **50** of the patrolling environment **10** during the patrol routine using the at least one imaging sensor **450**, **650**. In the example shown, the controller **500** schedules the patrolling routine for the robot **100** to capture human recognizable images **50** (still images or video) in the environment **10** using the at least one imaging sensor **450**, **650**, while maneuvering in the patrolling environment **10**. For example, while on patrol, the robot **100** senses a moving object **12**, determines the object **12** is a person **20**, and tracks the moving person **20** to get an image **50** and calculate a trajectory TR of the person **20**. To successfully capture an image **50** and calculate a trajectory TR, the controller **500** takes in to account the velocity of the robot **100**, the robot mass and center of gravity $CG_R$ for calculating deceleration, and a particular shutter speed and focal range of the imaging sensor **450** so that the imaging sensor **450** is properly positioned relative to the moving person **20** to capture a discernable still image and/or video clip for transmission to a remote user, such as the security system **1000**.

**[0153]** In some examples, the robot **100** captures human recognizable still images **50** of the environment **10** during repeating time cycles. Likewise, the robot **100** may continuously capture a video stream while maneuvering about the patrolling environment **10**. In some examples, the controller **500** schedules the patrolling routine for the robot **100** to capture human recognizable still images **50** at desired locations L, $L_{1-n}$ on the layout map **700**. For example, it may be desirable to obtain images **50** in high security areas of the patrolling environment **10** versus areas of less importance. The capture locations L may be defined by a location on the layout map **700** or may be defined by a location based on at least one of robot odometry, waypoint navigation, dead-reckoning, or a global positioning system. In some implementations, the robot **100** aims the field of view **452**, **652** of the imaging sensors **450**, **650** upon desired areas of the patrolling environment **10** through scanning to capture human recognizable still images and/or video of the desired areas, or to simply increase the field of view **452**, **652** coverage about the environment **10**. For example, the robot **100** may maneuver about travel corridors in the patrolling environment **10** and scan the imaging sensor **450**, **650** side-to-side with respect to a forward drive direction F of the robot **100** to increase a lateral field of view V-H of the imaging sensor **450**, **650** to obtain images and/or video **50** of rooms adjacent to the travel corridors. Moreover, the field of view **452**, **652** of the imaging sensor **450**, **650** may be aimed in a direction substantially normal to a forward drive direction F of the robot **100** or may be scanned to increase the corresponding field of view **452**, **652** (and/or perceive desired locations in the patrolling environment **10**).

**[0154]** The method **1200** may include, at operation **1208**, applying a location tag and a time tag to the captured image **50**. The location may define a location L on the layout map **700** or the location may be defined based on at least one of robot odometry, waypoint navigation, dead-reckoning, or a global positioning system. In some examples, the robot **100** (via the controller **500**) tags each image **50** (still image **50** and/or video) captured with the corresponding location and time. The robot **100** (via the controller **500**) may store the captured images **50** within the non-transitory memory **504** (FIG. **2**A). At operation **1210**, the method **1200** includes transmitting the images **50** and/or video and associated location/time tags in a surveillance report **1010** (e.g., FIG. **1**B) to the security system **1000** upon commencing or completing the patrolling routine or instantaneously after capturing each image **50** and/or video. For example, the robot **100** may communicate with the security system **1000** by transmitting emails, a text message, a short message service (SMS) message, or an automated voice mail including the captured images (or video) **50**. Other types of messages are possible as well, which may or may not be sent using the network **102**.

**[0155]** FIG. **13**A provides an exemplary arrangement of operations, executable on the controller **500**, for a method **1300** of operating a mobile robot **100** when an alarm A is triggered while the robot **100** navigates about a patrolling environment **10** using a layout map **700**. FIG. **13**B illustrates an example layout map **700** indicating a location of the alarm A, the robot **100**, and a person **20**. At operation **1302**, the method **1300** includes receiving the layout map **700** of the patrolling environment **10** (e.g., from the security system **1000** or another source), and at operation **1304**, maneuvering the robot **100** in the patrolling environment **10** according to a patrol routine (e.g., as discussed above, by moving to locations L on the layout map **700**). At operation **1306**, the method **1300** includes receiving a target location $L_2$ on the layout map **700** (e.g., from the security system **1000**), in response to an alarm A. The method **1300** includes, at operation **1308**, maneuvering the robot **100** to the target location $L_2$ to investigate the alarm A.

**[0156]** In the example shown, the robot **100** receives a signal indicating a triggered alarm A at an area in the patrolling environment **10**. The alarm A may include a proximity sensor, motion sensor, or other suitable sensor detecting presence of an object **12** and communicating with the security system **1000**. In the example shown, the robot **100** is driving in a forward drive direction F when the alarm A is triggered. The security system **1000** may receive an alarm signal S from the triggered alarm A and notify the robot **100** of the alarm A and provide a target location L, $L_2$ associated with a location of the alarm A. In some examples, the target location L defines a location on the layout map **700**. Additionally or alternatively, the target location L defines a location based on at least one of odometry, waypoint navigation, dead-reckoning, or a global positioning system. In some examples, the controller **500** issues one or more waypoints and/or drive commands to the drive system **200** to navigate the robot **100** to the target location L associated with the location $L_2$ of the alarm A. In the example shown, the one or more drive commands cause the robot **100** to turn 180 degrees from its current forward drive direction F and then navigate to the target location L, $L_2$ associated with the alarm A.

**[0157]** The method **1300** may include, at operation **1310**, determining if a person **20** is near the alarm location $L_2$. If a person **20** is not near the alarm, the method **1300** may include resuming with patrolling the environment **10** according the patrol routine. As discussed above, the controller **500** may determine the presence of a person **20** by noticing a moving object **12** and assuming the moving object **12** is a person **20**, by noticing an object **12** that meets a particular height range, or via pattern or image recognition. Other methods of people recognition are possible as well. If a person **20** is determined present, the method **1300** may include, at operation **1312**, capturing a human recognizable image **50** (still images **50** and/or video) of the person **20** using the image sensor(s) **450**, **650** of the robot **100**.

**[0158]** The robot **100** may use the imaging sensors **450** to detect objects **12** within the field of view **452**, **652** proximate the alarm A and detect if the object **12** is a person **20**. The robot **100**, via the controller **500**, using at least one imaging sensor **450**, **650**, may capture a human recognizable image **50** and/or video of the person **20** by considering the dynamic movement of the person **20** relative to the robot **100** and the limitations of the imaging sensor **450**, **650** (as discussed above), so that the captured image **50** is clear enough for a remote user (e.g., in communication with the security system **1000** and/or the robot **100**) to identify an alarm situation or a non-alarm situation and so that the image **50** is useful for identifying the person(s) **20** moving in the patrolling environment **10**. As discussed above with reference to FIG. **11**, the controller **500** may execute one or more of person tracking **1112**, person following **1114**, and imaging capturing **1116** to move the robot **100** and/or the imaging sensor(s) **450**, **650** relative to the person **20**, so that the robot **100** can capture clear images **50** of the person **20**, especially when the person **20** may be moving (e.g., running away from the location of the robot **100**). In some examples, the controller **500** commands the robot **100** to track and/or follow the identified person **20** to further monitor activities of the person **20**.

**[0159]** The method **1300** may include, at operation **1314**, transmitting a surveillance report **1010** to the security system and/or a remote user or entity. As previously discussed, the robot **100** may tag the image(s) **50** with a corresponding location and a time associated with the captured image **50** and/or video and transmit the tagged image **50** to the security system **1000** in a surveillance report **1010** (FIG. **1**B). Moreover, the robot **100** may store the tagged image **50** in the non-transitory memory **504**.

**[0160]** Referring to FIGS. **14**A-**14**D, in some implementations, the controller **500** executes the aiming behavior **530*e*** to effectuate two goals: 1) aiming the field of view **452**, **652** of the imaging sensor **450**, **650** to continuously perceive the person **20**, as shown in FIG. **14**A, and maintaining the aimed field of view **452**, **652** on the person **20** (e.g., moving the robot **100** holonomically with respect to the person **20** and/or aiming the imaging sensor **450**, **650** with respect to the person **20**) so that that the center of the field of view **452**, **652** continuously perceives the person **20**, as shown in FIGS. **14**B and **14**C. For instance, FIG. **14**B shows the controller **500** issuing drive commands to the drive system **200**, causing the robot **100** to move in the planar direction with respect to the movement trajectory TR associated with the person **20**. Likewise, FIG. **14**C shows the controller **500** commanding the at least one imaging sensor **450**, **650** to move with respect to the movement trajectory TR (e.g., at least one of rotate, pan, or tilt) and planar velocity of the robot **100**. After the robot **100** captures a human recognizable image **50** and/or video of the person **20**, the controller **500** may issue drive commands to the drive system **200**, causing the robot **100** to turn and drive away from the person **20** or continue tracking and following the person **20**, as described above.

**[0161]** FIG. **15** provides an exemplary arrangement of operations for a method **1500** of capturing one or more images **50** (or video) of a person **20** identified in a patrolling environment **10** of the robot **100**. The method **1500** may be executed by the controller **500** (e.g., computing device). The controller **500** may be the robot controller or a controller external to the robot **100** that communicates therewith. At operation **1502**, the method **1500** includes aiming the field of view **452**, **652** of at least one imaging sensor **450**, **650** to continuously perceive an identified person **20** in the corresponding field of view **452**, **652**. At operation **1504**, the method **1500** includes capturing a human recognizable image **50** (or video) of the person **20** using the imaging sensor(s) **450**, **650**. For example, for operation **1502** and/or **1504**, the controller **500** may execute the dynamic image capture routine **1110** (FIG. **11**) to capture clear images **50** of the person **20**, which may be moving with respect to the robot **100**. The dynamic image capture routine **1110** may include executing one or more of person tracking **1112**, person following **1114**, aiming **1116** of image sensor(s) **450** or image capturing **1118**, so that the robot **100** can track the person, control its velocity, aim its imaging sensor(s) and capture clear images **50** of the person **20**, while the person **20** and/or the robot **100** are moving with respect to each other. The controller **500** may accommodate for limitations of the imaging sensor **450** by maneuvering the robot **100** based on a trajectory TR of the person **20** to capture image data **50** (e.g., still images or video) of the person **20** along a field of view **452** of the imaging sensor **450**. The controller **500** may account for dynamics of the person **20** (e.g., location, heading, trajectory, velocity, etc.), shutter speed of the imaging sensor **450** and dynamics of the robot **100** (e.g., velocity/holonomic motion) to aim the corresponding field of view **452** of the imaging sensor **450** to continuously perceive the person **20** within the field of view **452**, so that the person **20** is centered in the captured image **50** and the image **50** is clear. Moreover, the controller **500** may execute movement commands to maneuver the robot **100** in relation to the location of the person **20** to capture a crisp image **50** of a facial region of the person **20**, so that the person **20** is recognizable in the image **50**. In some examples, the controller **500** associates a location tag and/or a time tag with the image **50**. At operation **1506**, the controller **500** reviews the captured image **50** to determine if the identified person **20** is perceived in the center of the captured image **50** or if the captured image **50** is clear. When the identified person **20** is perceived in the center of the image **50** and the image **50** is clear, the method **1500** includes, at operation **1508** storing the captured image **50** in non-transitory memory **504** (FIG. **2**A) in communication with the controller **500** and, at operation **1510**, transmitting the captured image **50**, e.g., in a surveillance report **1010**, to the security system **1000** or another remote recipient in communication with the controller **500**. In some examples, the controller **500** retrieves one or more captured images **50** from the non-transitory memory **504** and transmits the one or more captured images **50** to security system **1000**. In other examples, at operation **1508**, the controller **500** simultaneously stores a captured image **50** and transmits the captured image **50** to the security system **1000** upon capturing the image **50**. However, when the identified person **20** is perceived outside the center of the image **50** or the image **50** is blurred, the method **1500** includes repeating operations **1502**-**1506** to re-aim the field of view **452**, **652** of the at least one imaging sensor **450**, **650** to continuously perceive the identified person **20** in the field of view **452**, **652**, capture a subsequent human recognizable image **50** of the identified person **20** using the at least one imaging sensor **450**, **650** and review the captured image **50** to see if the person **20** is at least in or centered in the image **50**. The security system **1000** and/or remote recipient of the surveillance report **1010** may review the image(s) **50** in lieu of the robot **100** or in addition to the robot **100** to further assess a nature of the image(s) **50** (e.g., whether the image(s) **50** raises a security concern). In some examples, the controller **500** and/or the security system **1000** executes one or more image enhancement routines to make the image(s) **50** more clear, to crop the image(s) **50** around objects of interest, or other image manipulations.

**[0162]** While operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. In certain circumstances, multi-tasking and parallel processing may be advantageous. Moreover, the separation of various system components in the embodiments described above should not be understood as requiring such separation in all embodiments, and it should be understood that the described program components and systems can generally be integrated together in a single software product or packaged into multiple software products.

**[0163]** 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. For example, the actions recited in the claims can be performed in a different order and still achieve desirable results.

What is claimed is:

**1**. A method of operating a mobile robot, the method comprising:

receiving, at a computing device, a layout map corresponding to a patrolling environment;

maneuvering the robot in the patrolling environment based on the received layout map;

receiving, at the computing device, imaging data of a scene about the robot when the robot maneuvers in the patrolling environment, the imaging data received from at least one imaging sensor disposed on the robot and in communication with the computing device;

identifying, by the computing device, a person in the scene based on the received imaging data;

aiming, by the computing device, a field of view of the at least one imaging sensor to continuously perceive the identified person in the field of view based on robot dynamics, person dynamics comprising a movement trajectory of the person, and imaging sensor dynamics of the at least one imaging sensor; and

capturing, by the computing device, a human recognizable image of the identified person using the at least one imaging sensor.

**2**. The method of claim **1**, further comprising:

segmenting, by the computing device, the received imaging data into objects;

filtering, by the computing device, the objects to remove objects greater than a first threshold size comprising a first height of about 8 feet and smaller than a second threshold size comprising a second height of about 3 feet; and

identifying, by the computing device, the person in the scene corresponding to at least a portion of the filtered objects.

**3**. The method of claim **1**, further comprising at least one of:

aiming, by the computing device, the at least one imaging sensor to maintain the corresponding aimed field of view on a facial region of the identified person; or

commanding, by the computing device, holonomic motion of the robot to maintain the aimed field of view of the at least one imaging sensor on the facial region of the identified person.

**4**. The method of claim **1**, further comprising using, by the computing device, a Kalman filter to track and propagate the movement trajectory of the identified person.

**5**. The method of claim **4**, further comprising commanding, by the computing device, the robot to move in a planar direction with three planar degrees of freedom while maintaining the aimed field of view of the at least one imaging sensor on the identified person associated with the movement trajectory.

**6**. The method of claim **5**, wherein the robot moves in the planar direction at a velocity proportional to the movement trajectory of the identified person.

**7**. The method of claim **4**, further comprising commanding, by the computing device, at least one of panning or tilting the at least one imaging sensor to maintain the aimed field of view of the at least one imaging sensor on the identified person associated with the movement trajectory.

**8**. The method of claim **1**, further comprising:

reviewing, by the computing device, the captured image to determine whether or not the identified person is perceived in a center of the image or the image is clear;

when the identified person is perceived in the center of the image and the image is clear:

storing the captured image in non-transitory memory in communication with the computing device; and

transmitting, by the computing device, the captured image to a security system in communication with the computing device; and

when the identified person is perceived outside the center of the image or the image is blurred:

re-aiming the field of view of the at least one imaging sensor to continuously perceive the identified person in the field of view; and

capturing a subsequent human recognizable image of the identified person using the at least one imaging sensor,

wherein the imaging sensor dynamics comprise a threshold rotational velocity of the imaging sensor relative to an imaging target to capture a clear image of the imaging target.

**9**. The method of claim **1**, further comprising:

applying, by the computing device, a location tag to the captured image associated with a location of the identified person;

applying, by the computing device, a time tag associated with a time the image was captured; and

transmitting a tagged layout map from the computing device to a remote device.

**10**. The method of claim **9**, wherein the location tag defines a location on the layout map.

**11**. The method of claim **1**, wherein the at least one imaging sensor comprises at least one of a still-image camera, a video camera, a stereo camera, or a three-dimensional point cloud imaging sensor.

**12**. The method of claim **1**, wherein the robot dynamics comprise:

a first acceleration/deceleration limit of a drive system of the robot;

a second acceleration/deceleration limit associated with a drive command; and

a deceleration limit associated with a stop command.

**13**. A robot comprising:

a robot body;

a drive system supporting the robot body and configured to maneuver the robot over a floor surface of a patrolling environment, the drive system having a forward drive direction;

at least one imaging sensor disposed on the robot body; and

a controller in communication with the drive system and the at least one imaging sensor, the controller:

receiving a layout map corresponding to a patrolling environment;

issuing drive commands to the drive system to maneuver the robot in the patrolling environment based on the received layout map;

receiving imaging data from the at least one imaging sensor of a scene about the robot when the robot maneuvers in the patrolling environment;

identifying a moving target in the scene based on the received imaging data;

propagating a movement trajectory of the identified moving target based on the received imaging data;

aiming a field of view of the at least one imaging sensor to continuously perceive the identified moving target in the field of view; and

capturing a human recognizable image of the identified moving target using the at least one imaging sensor.

**14**. The robot of claim **13**, wherein the controller:

segments the received imaging data into objects;

filters the objects to remove objects greater than a first threshold size comprising a first height of about 8 feet and smaller than a second threshold size comprising a second height of about 3 feet; and identifies a person in the scene as the identified moving target corresponding to at least a portion of the filtered objects.

**15**. The robot of claim **14**, further comprising a rotator and a tilter disposed on the robot body in communication with the controller, the rotator and tilter providing at least one of panning and tilting of the at least one imaging sensor, wherein the controller at least one of:

commands the rotator or tilter to at least one of pan or tilt the at least one imaging sensor to maintain the corresponding aimed field of view on a facial region of the identified person; or

issues drive commands to the drive system to holonomically move the robot to maintain the aimed field of view of the at least one imaging sensor on the facial region of the identified person.

**16**. The robot of claim **15**, wherein the controller commands the drive system to drive in a planar direction with three planar degrees of freedom at a velocity proportional to the movement trajectory of the identified moving target while maintaining the aimed field of view of the at least one imaging sensor on the identified moving target associated with the movement trajectory.

**17**. The robot of claim **13**, further comprising a rotator and a tilter disposed on the robot body and in communication with the controller, the rotator and tilter providing at least one of panning and tilting of the at least one imaging sensor, wherein the controller commands the rotator or the tilter to at least one of pan or tilt the at least one imaging sensor to maintain the aimed field of view of the at least one imaging sensor on the identified moving target associated with the movement trajectory, wherein the least one of the commanded panning or tilting is at a velocity proportional to the movement trajectory of the identified moving target and proportional to a planar velocity of the robot.

**18**. The robot of claim **13**, wherein the controller reviews the captured image to determine whether the identified moving target is perceived in a center of the image or the image is clear;

when the identified moving target is perceived in the center of the image and the image is clear, the controller:

stores the captured image in non-transitory memory in communication with the controller; and

transmits the captured image to a security system in communication with the controller; and

when the identified moving target is perceived outside the center of the image or the image is blurred, the controller:

re-aims the field of view of the at least one imaging sensor continuously perceive the identified moving target in the field of view; and

captures a subsequent human recognizable image of the identified moving target using the at least one imaging sensor.

**19**. The robot of claim **13**, wherein the controller:

applies a location tag to the captured image associated with a location of the identified moving target, the location tag defining a location on the layout map based on at least one of robot odometry, waypoint navigation, dead-reckoning, or a global positioning system; and

applies a time tag associated with a time the image was captured.

**20**. The robot of claim **13**, wherein the at least one imaging sensor comprises at least one of a still-image camera, a video camera, a stereo camera, or a three-dimensional point cloud imaging sensor.

**21**. The robot of claim **13**, wherein the controller aims the at least one imaging sensor based on acceleration/deceleration limits of the drive system and a latency between sending an image capture request to the at least one imaging sensor and the at least one imaging sensor capturing an image, wherein the acceleration/deceleration limits of the drive system comprise an acceleration/deceleration limit associated with a drive command and a deceleration limit associated with a stop command.

**22**. The robot of claim **21**, wherein the controller determines a movement trajectory of the identified moving target and aims the at least one imaging sensor based on the movement trajectory of the identified moving target.

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