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(54) **ALIGNING GEODATA GRAPH OVER ELECTRONIC MAPS**

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G06T 7/30 (2017.01)

(52) **U.S. Cl.**
CPC ***G06T 7/30*** (2017.01); *G06T 2207/10028* (2013.01); *G06T 2207/30248* (2013.01)

(58) **Field of Classification Search**
CPC G06T 7/30; G06T 2207/10028; G06T 2207/30248; G06T 7/33; G01C 21/00; G01C 21/3815; G06V 10/44; G06V 10/454; G06V 10/82; G06V 20/56
See application file for complete search history.

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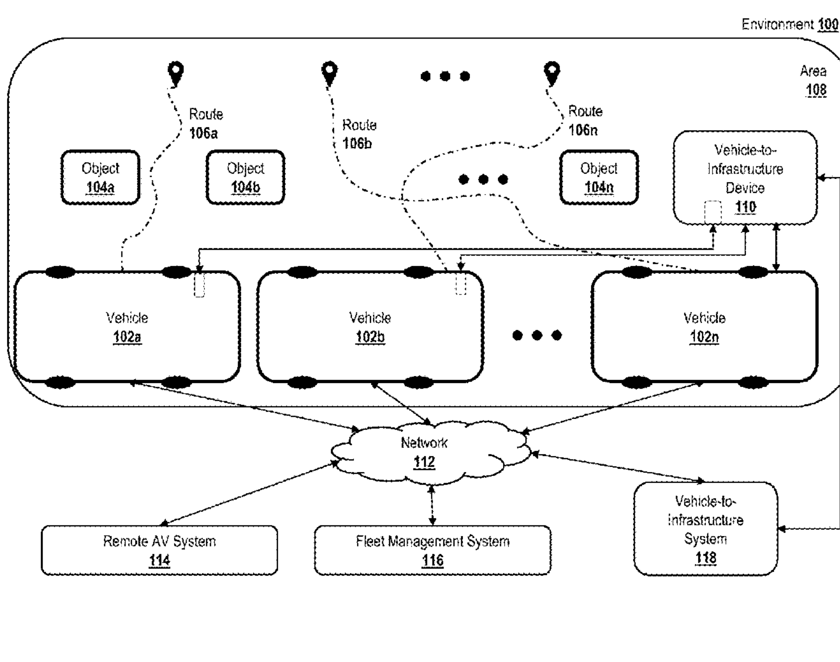
(57) **ABSTRACT**

Provided are methods for aligning a raster map of a geographic area with a geodata map of the geographic area. A method includes obtaining, using at least one processor, the raster map of the geographic area. A distance map corresponding to the raster map of the geographic area may be generated. The raster map may be aligned with a geodata map of the geographic area by deforming the geodata map relative to the distance map in order to maximize a coverage of the geodata map over the raster map. An updated geodata map of the geographic area may be generated based on the aligning. Related systems and computer program products are also provided.

20 Claims, 15 Drawing Sheets



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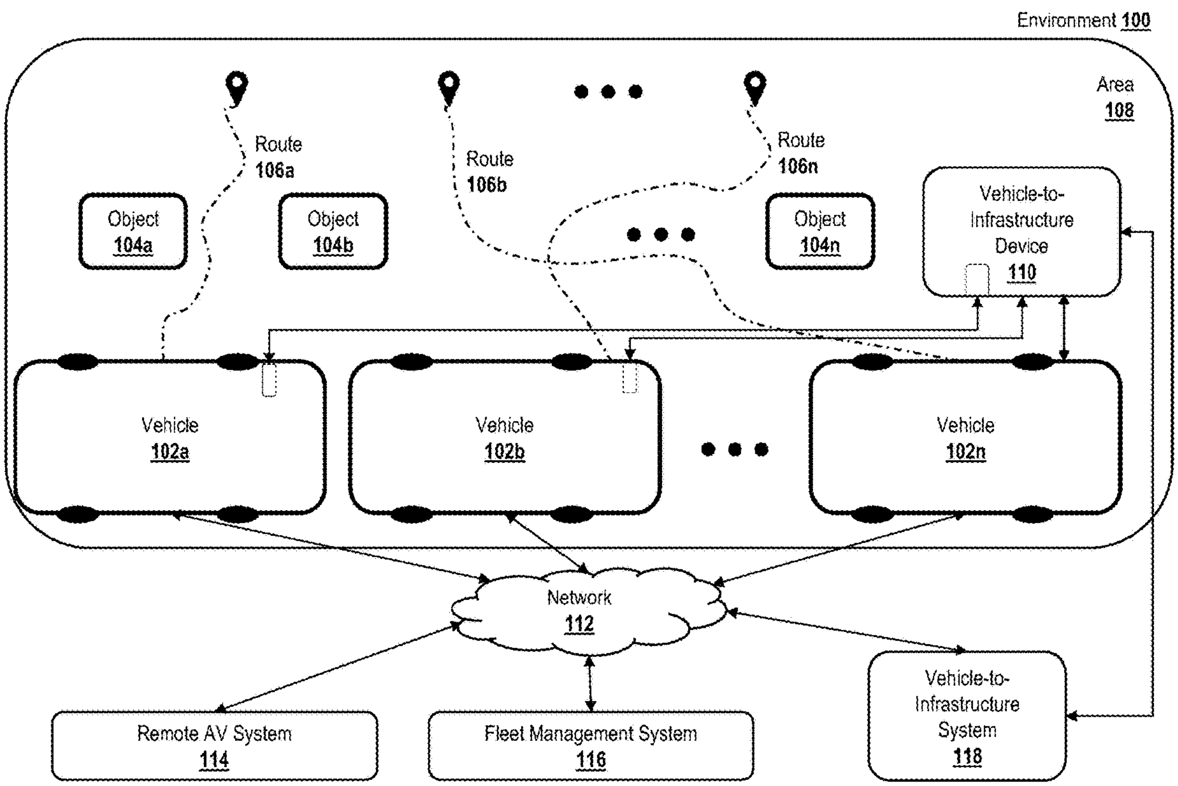

Environment 100
Area 108
Route 106a
Route 106b
Route 106n
Object 104a
Object 104b
Object 104n
Vehicle-to-Infrastructure Device 110
Vehicle 102a
Vehicle 102b
Vehicle 102n
Network 112
Remote AV System 114
Fleet Management System 116
Vehicle-to-Infrastructure System 118

FIG. 1

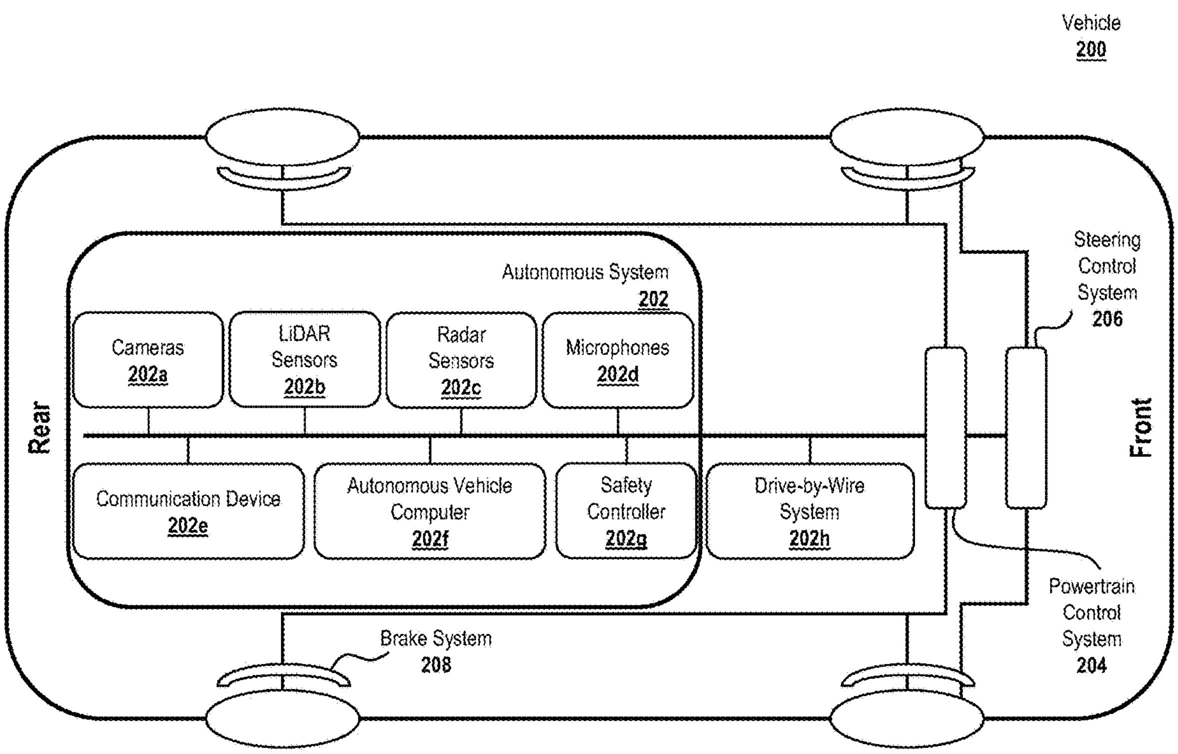

Vehicle
200
Autonomous System
202
Cameras
202a
LiDAR
Sensors
202b
Radar
Sensors
202c
Microphones
202d
Rear
Front
Communication Device
202e
Autonomous Vehicle
Computer
202f
Safety
Controller
202g
Drive-by-Wire
System
202h
Steering
Control
System
206
Powertrain
Control
System
204
Brake System
208

FIG. 2

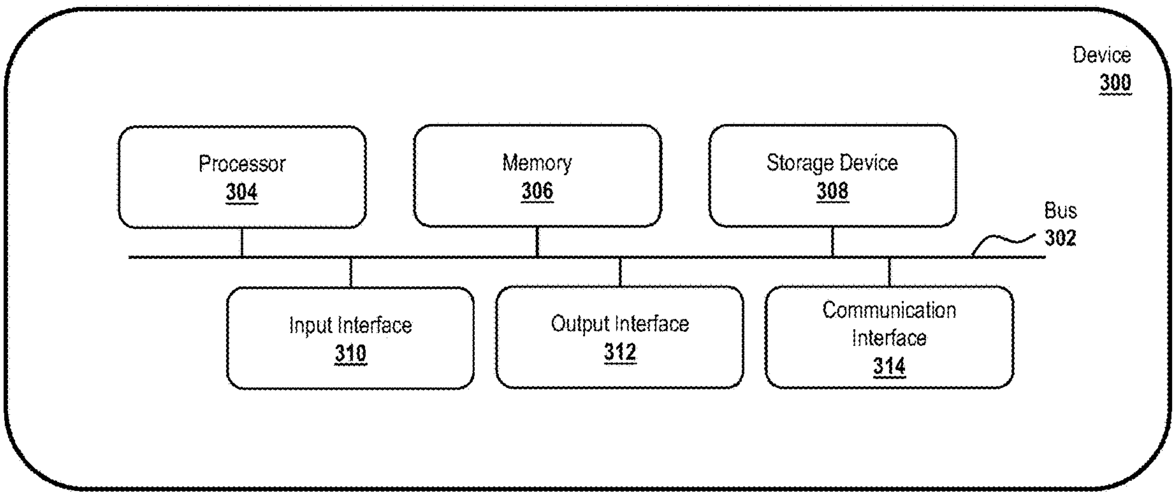

Device
300
Processor
304
Memory
306
Storage Device
308
Bus
302
Input Interface
310
Output Interface
312
Communication
Interface
314

FIG. 3

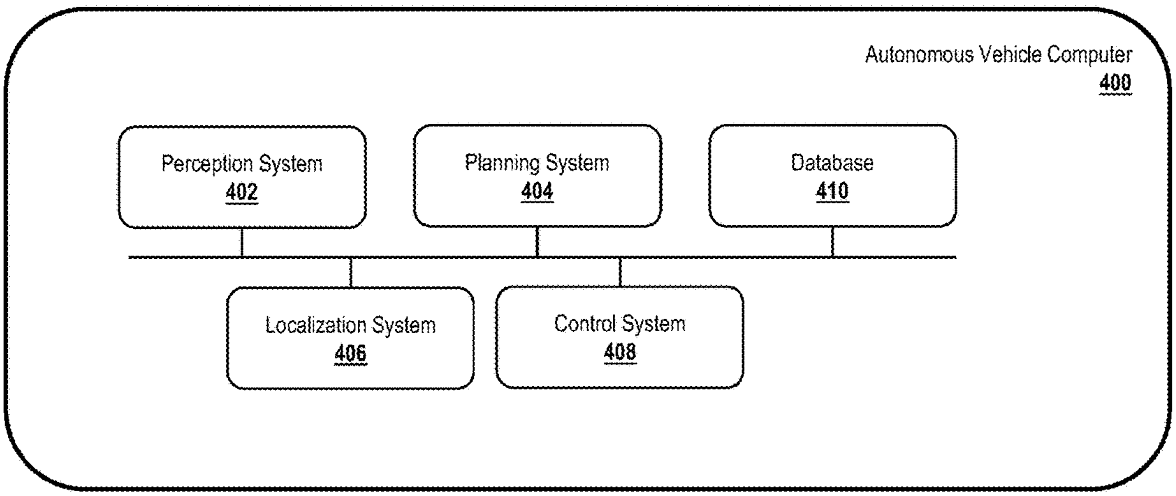
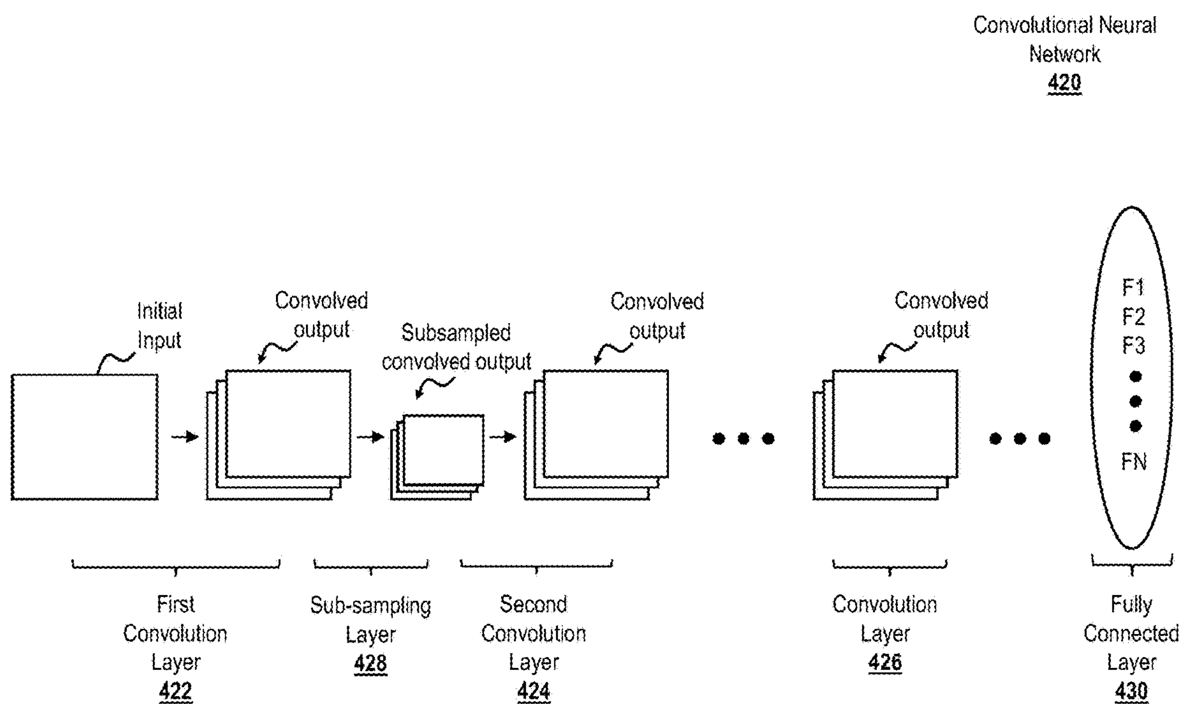

Autonomous Vehicle Computer
400
Perception System
402
Planning System
404
Database
410
Localization System
406
Control System
408

FIG. 4A



Convolutional Neural
Network
420
Initial
Input
Convolved
output
Subsampled
convolved output
Convolved
output
Convolved
output
F1
F2
F3
FN
First
Convolution
Layer
422
Sub-sampling
Layer
428
Second
Convolution
Layer
424
Convolution
Layer
426
Fully
Connected
Layer
430

FIG. 4B

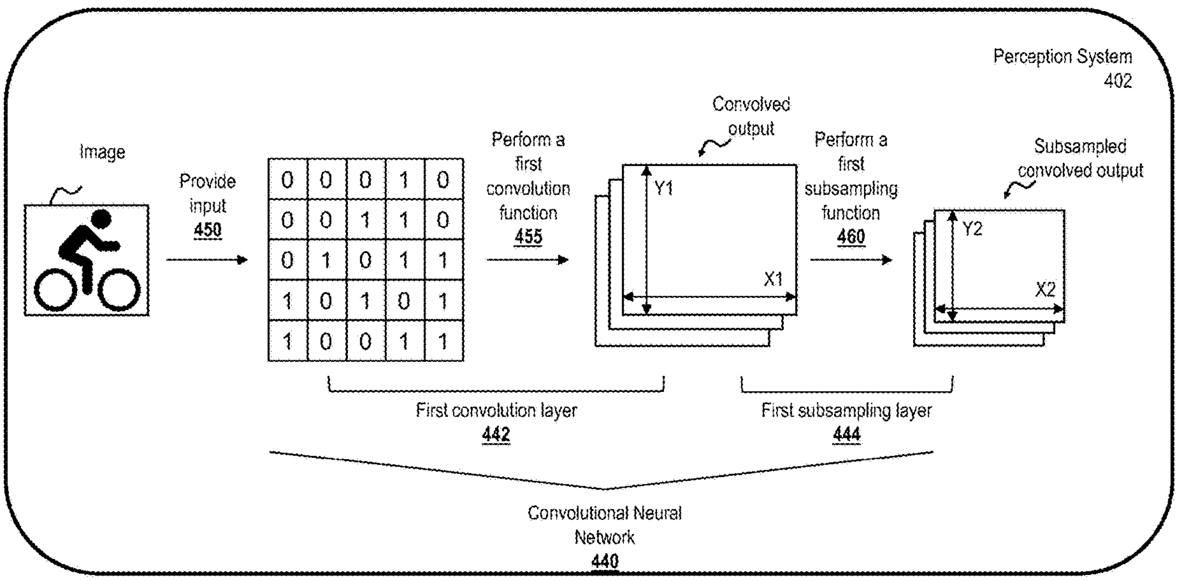
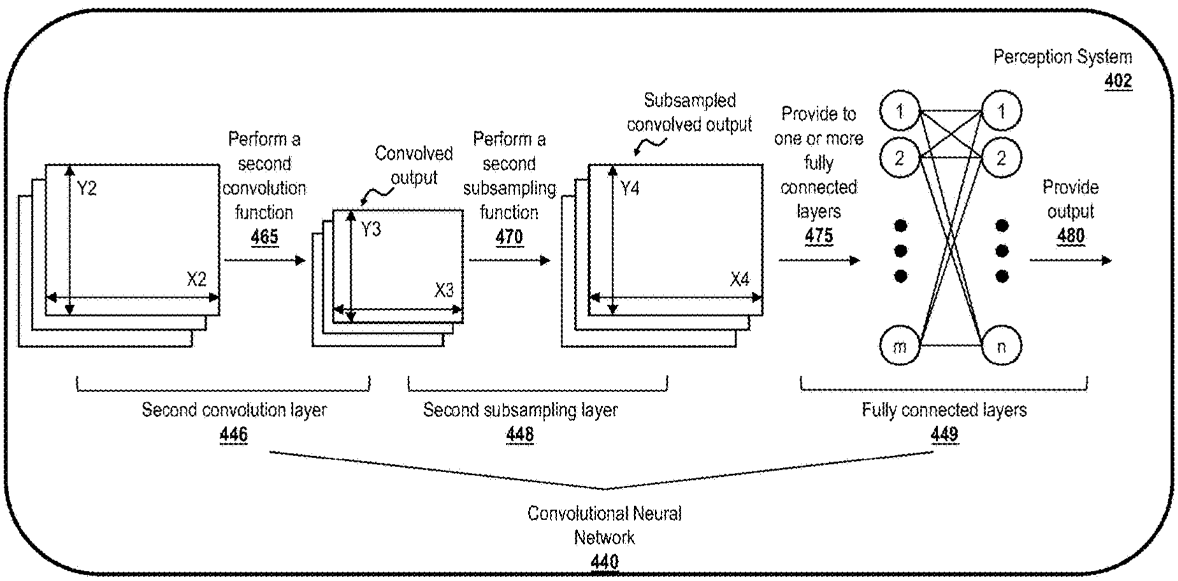

Perception System
402
Image
Provide
input
450
0 0 0 1 0
0 0 1 1 0
0 1 0 1 1
1 0 1 0 1
1 0 0 1 1
Perform a
first
convolution
function
455
Convolved
output
Y1
X1
Perform a
first
subsampling
function
460
Subsampled
convolved output
Y2
X2
First convolution layer
442
First subsampling layer
444
Convolutional Neural
Network
440

FIG. 4C



Perception System
402
Perform a second convolution function
465
Convolved output
Perform a second subsampling function
470
Subsampled convolved output
Provide to one or more fully connected layers
475
Provide output
480
Y2
X2
Y3
X3
Y4
X4
1
2
m
1
2
n
Second convolution layer
446
Second subsampling layer
448
Fully connected layers
449
Convolutional Neural Network
440

FIG. 4D

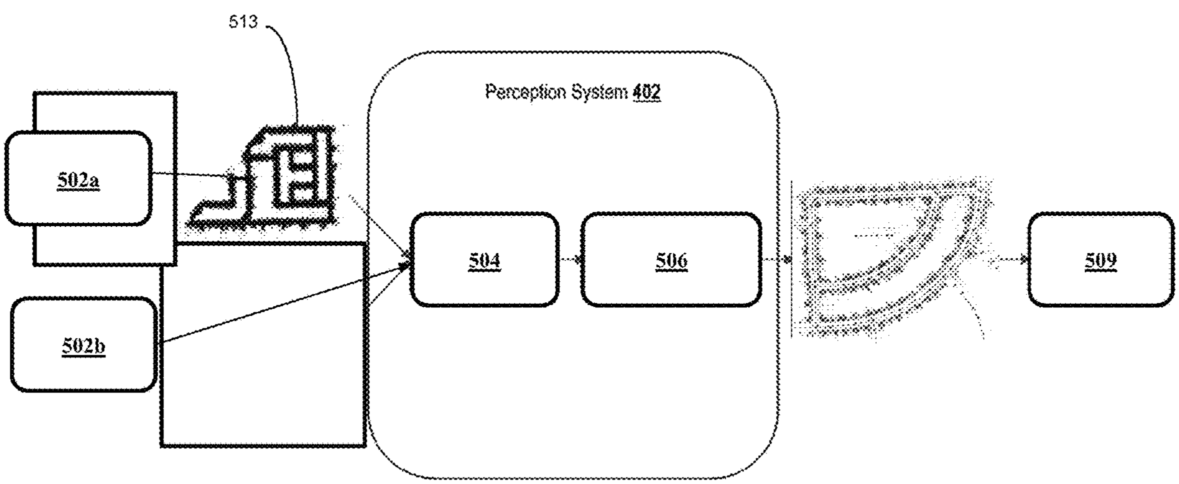


FIG. 5A

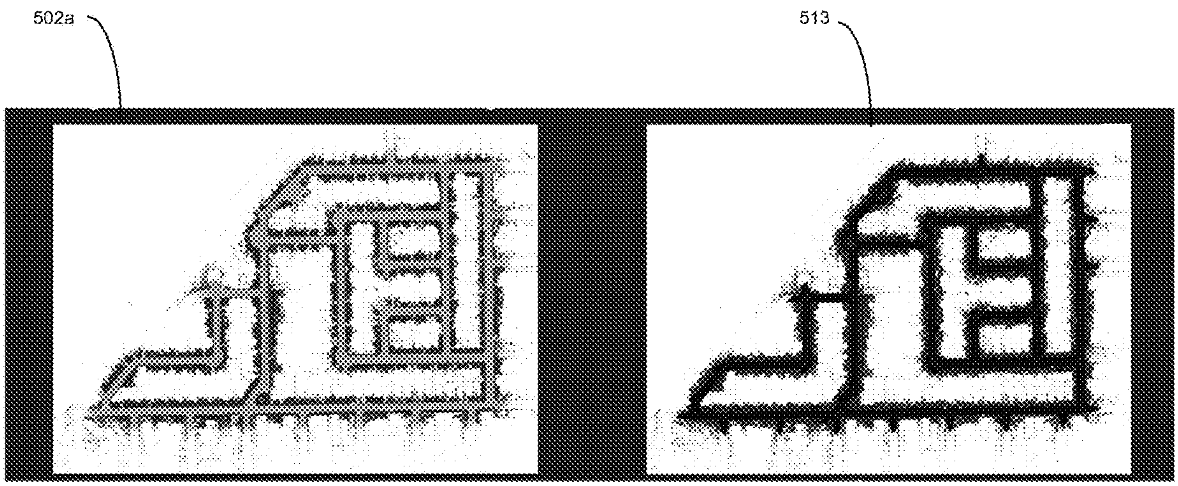


FIG. 5B

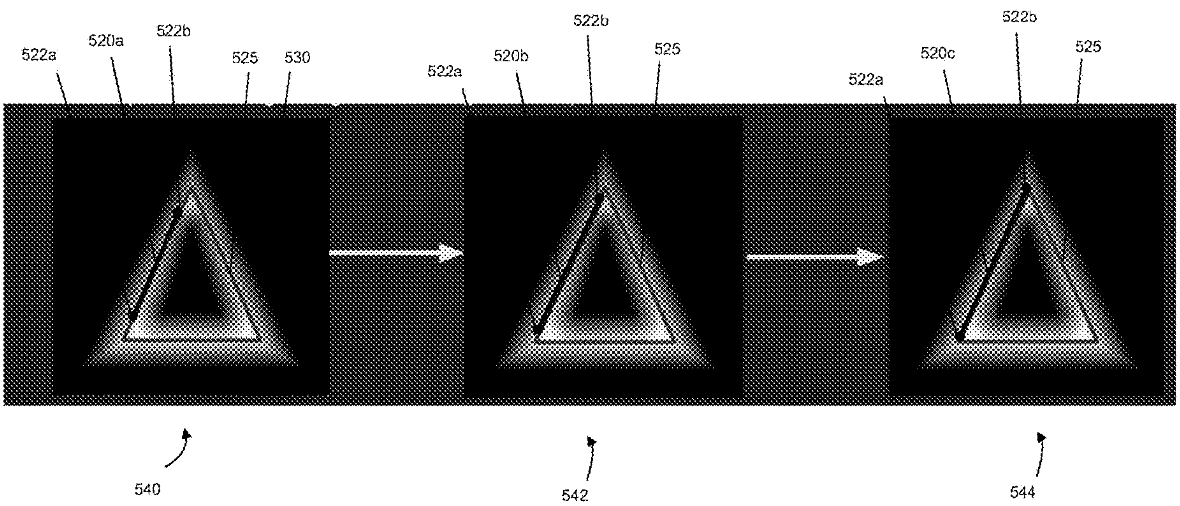
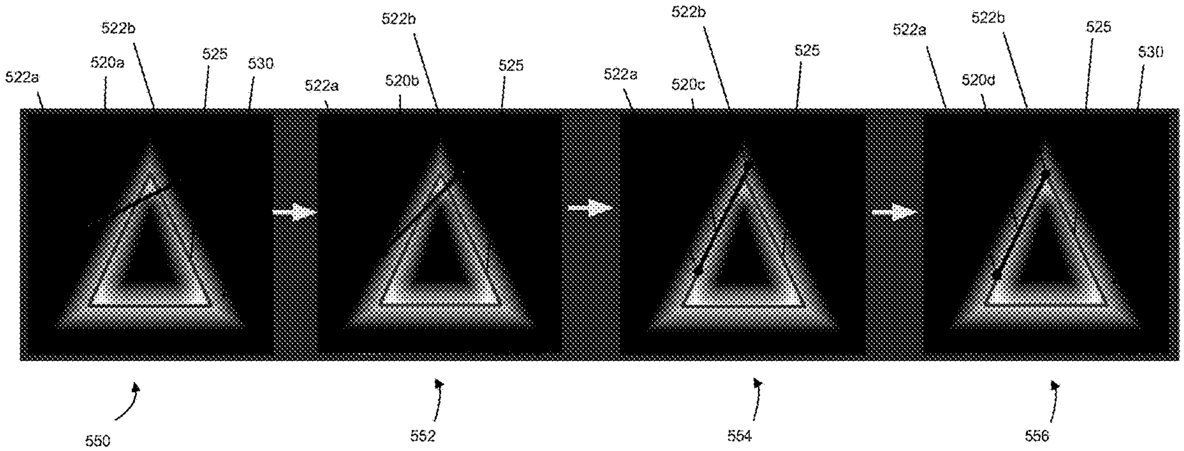

522a
520a
522b
525
530
522a
520b
522b
525
522a
520c
522b
525
540
542
544

FIG. 5C



522a
520a
522b
525
530
522a
520b
522b
525
522a
520c
522b
525
522a
520d
522b
525
530
550
552
554
556

FIG. 5D

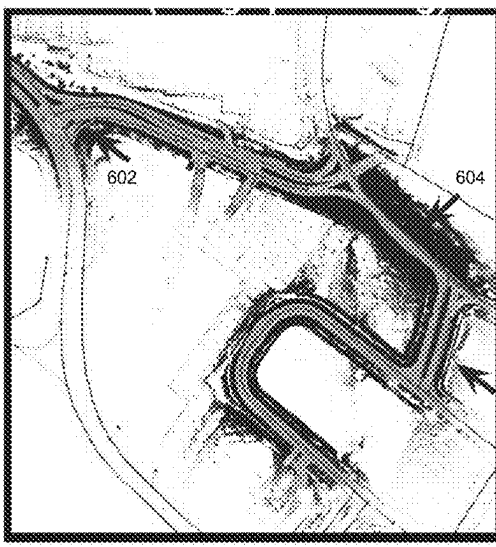


FIG. 6A

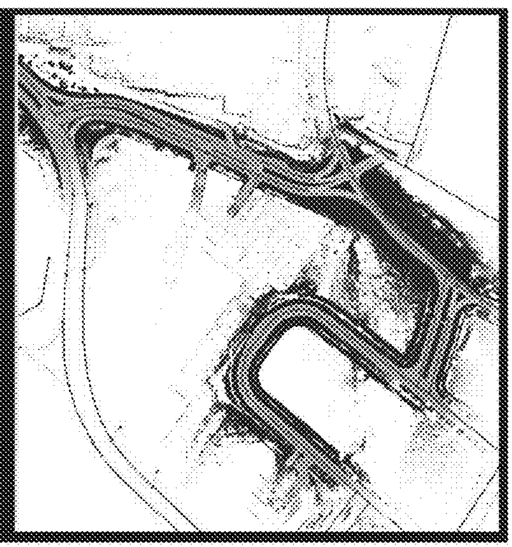


FIG. 6B

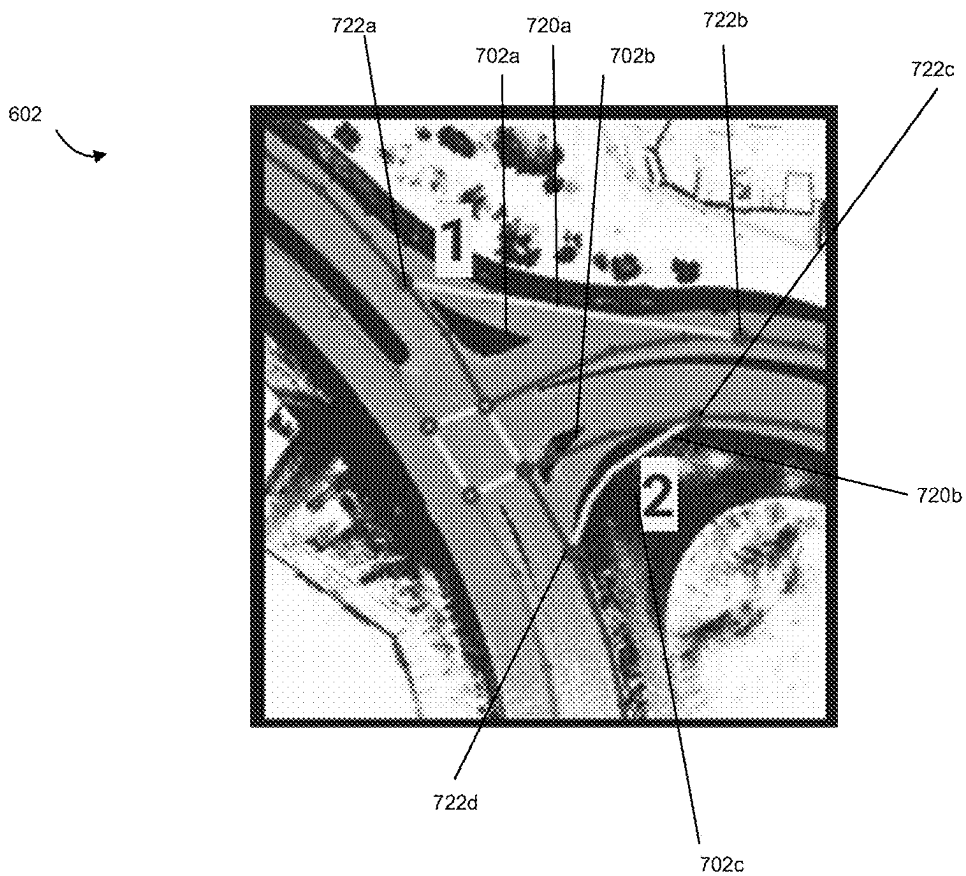


FIG. 7

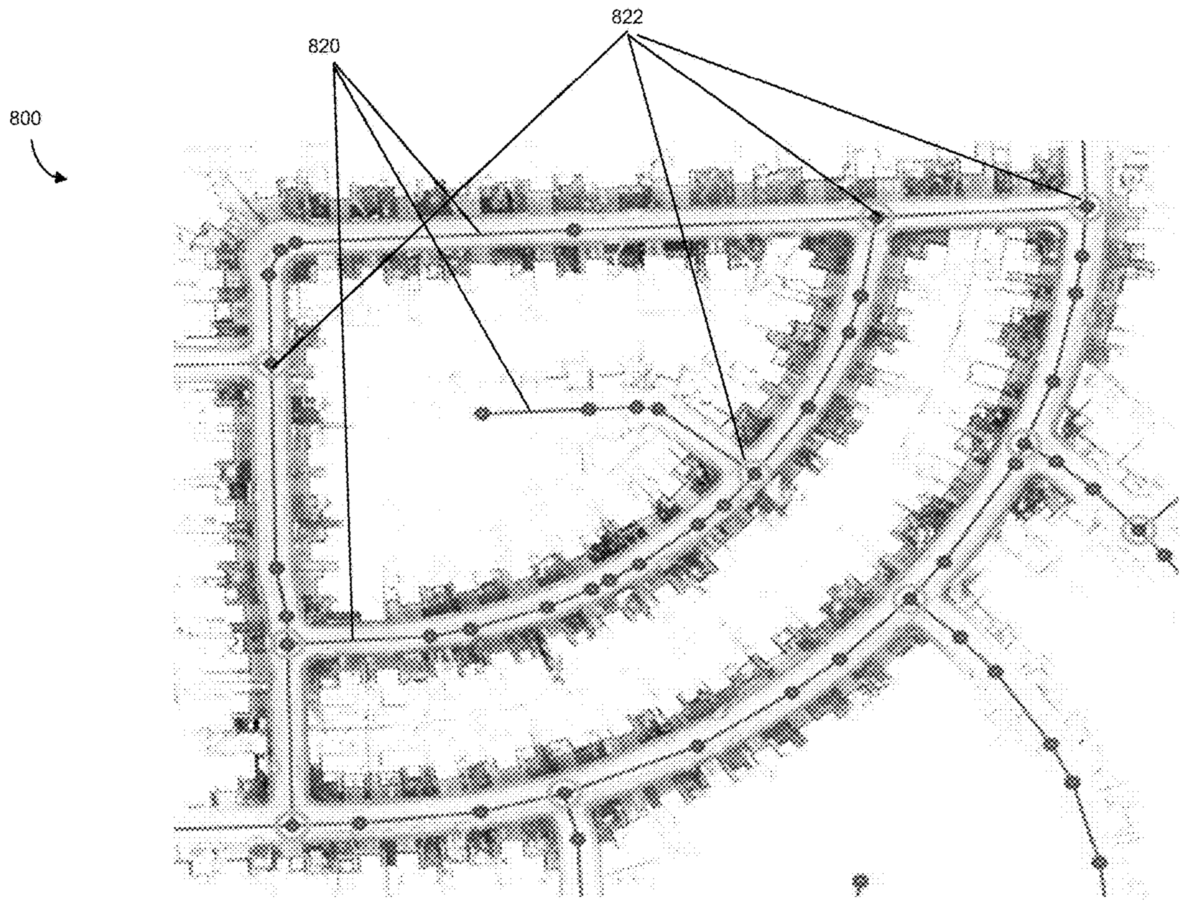


FIG. 8

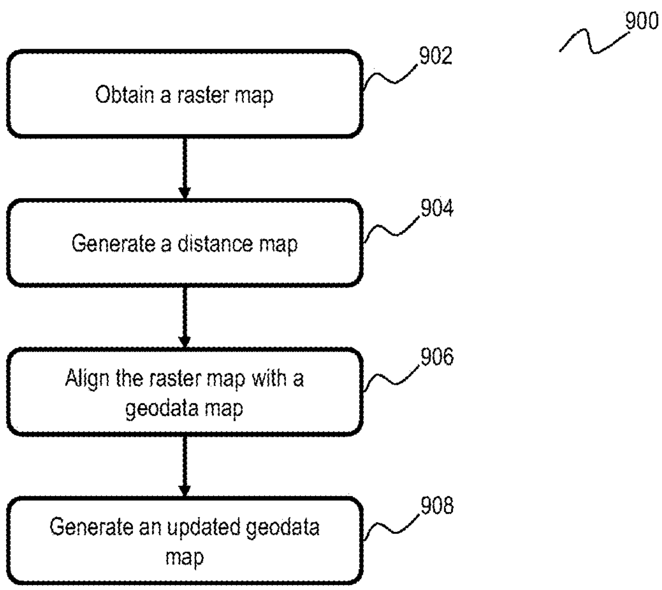

900
902
Obtain a raster map
904
Generate a distance map
906
Align the raster map with a geodata map
908
Generate an updated geodata map

FIG. 9

ALIGNING GEODATA GRAPH OVER ELECTRONIC MAPS

CROSS REFERENCE TO RELATED APPLICATION

This application claims priority to U.S. Provisional Application No. 63/302,436, entitled "ALIGNING GEODATA GRAPH OVER ELECTRONIC MAPS" and filed on Jan. 24, 2022, the disclosure of which is incorporated herein by reference in its entirety.

BACKGROUND

An autonomous vehicle may be capable of sensing its surrounding environment and navigating with minimal to no human input. In order to safely traverse a selected path while avoiding obstacles that may be present along the way, the vehicle may rely on various types of maps. Examples of maps include a raster map in which physical features are represented by pixels and a geodata map (or graph-based geographic data) in which traffic lanes are represented as edges (e.g., undirected edges) and intersections between two or more traffic lanes are represented as nodes. The maps may include semantic labels that enable the vehicle to distinguish between different physical features present in the vehicle's surrounding environment. However, some maps, such as geodata maps, may exhibit metric inconsistencies, which may diminish the accuracy and consistency of downstream tasks including annotation, navigation, localization, and/or the like.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** is an example environment in which a vehicle including one or more components of an autonomous system can be implemented;

FIG. **2** is a diagram of one or more systems of a vehicle including an autonomous system;

FIG. **3** is a diagram of components of one or more devices and/or one or more systems of FIGS. **1** and **2**;

FIG. **4**A is a diagram of certain components of an autonomous system;

FIG. **4**B is a diagram of an implementation of a neural network;

FIGS. **4**C and **4**D are a diagram illustrating example operation of a convolutional neural network (CNN); and

FIG. **5**A is a block diagram illustrating an example of a perception system for generating an updated geodata map for a geographic area;

FIG. **5**B depicts an example of a raster map of a geographic area and a corresponding distance map;

FIG. **5**C is a diagram illustrating an example process for reducing a range error between a distance map and a geodata map;

FIG. **5**D is a diagram illustrating an example process for reducing a coverage error between a distance map and a geodata map;

FIG. **6**A is a diagram illustrating an example initial geodata map;

FIG. **6**B is a diagram illustrating an example updated geodata map;

FIG. **7** is a diagram illustrating an example non-rigid transformation of a geodata map;

FIG. **8** is a diagram illustrating an example alignment of a geodata graph with a raster map; and

FIG. **9** is a flowchart of a process for alignment of a geodata graph over raster maps.

DETAILED DESCRIPTION

In the following description numerous specific details are set forth in order to provide a thorough understanding of the present disclosure for the purposes of explanation. It will be apparent, however, that the embodiments described by the present disclosure can be practiced without these specific details. In some instances, well-known structures and devices are illustrated in block diagram form in order to avoid unnecessarily obscuring aspects of the present disclosure.

Specific arrangements or orderings of schematic elements, such as those representing systems, devices, modules, instruction blocks, data elements, and/or the like are illustrated in the drawings for ease of description. However, it will be understood by those skilled in the art that the specific ordering or arrangement of the schematic elements in the drawings is not meant to imply that a particular order or sequence of processing, or separation of processes, is required unless explicitly described as such. Further, the inclusion of a schematic element in a drawing is not meant to imply that such element is required in all embodiments or that the features represented by such element may not be included in or combined with other elements in some embodiments unless explicitly described as such.

Further, where connecting elements such as solid or dashed lines or arrows are used in the drawings to illustrate a connection, relationship, or association between or among two or more other schematic elements, the absence of any such connecting elements is not meant to imply that no connection, relationship, or association can exist. In other words, some connections, relationships, or associations between elements are not illustrated in the drawings so as not to obscure the disclosure. In addition, for ease of illustration, a single connecting element can be used to represent multiple connections, relationships or associations between elements. For example, where a connecting element represents communication of signals, data, or instructions (e.g., "software instructions"), it should be understood by those skilled in the art that such element can represent one or multiple signal paths (e.g., a bus), as may be needed, to affect the communication.

Although the terms first, second, third, and/or the like are used to describe various elements, these elements should not be limited by these terms. The terms first, second, third, and/or the like are used only to distinguish one element from another. For example, a first contact could be termed a second contact and, similarly, a second contact could be termed a first contact without departing from the scope of the described embodiments. The first contact and the second contact are both contacts, but they are not the same contact.

The terminology used in the description of the various described embodiments herein is included for the purpose of describing particular embodiments only and is not intended to be limiting. As used in the description of the various described embodiments and the appended claims, the singular forms "a," "an" and "the" are intended to include the plural forms as well and can be used interchangeably with "one or more" or "at least one," unless the context clearly indicates otherwise. It will also be understood that the term "and/or" as used herein refers to and encompasses any and all possible combinations of one or more of the associated listed items. It will be further understood that the terms "includes," "including," "comprises," and/or "comprising," when used in this description specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

As used herein, the terms "communication" and "communicate" refer to at least one of the reception, receipt, transmission, transfer, provision, and/or the like of information (or information represented by, for example, data, signals, messages, instructions, commands, and/or the like). For one unit (e.g., a device, a system, a component of a device or system, combinations thereof, and/or the like) to be in communication with another unit means that the one unit is able to directly or indirectly receive information from and/or send (e.g., transmit) information to the other unit. This may refer to a direct or indirect connection that is wired and/or wireless in nature. Additionally, two units may be in communication with each other even though the information transmitted may be modified, processed, relayed, and/or routed between the first and second unit. For example, a first unit may be in communication with a second unit even though the first unit passively receives information and does not actively transmit information to the second unit. As another example, a first unit may be in communication with a second unit if at least one intermediary unit (e.g., a third unit located between the first unit and the second unit) processes information received from the first unit and transmits the processed information to the second unit. In some embodiments, a message may refer to a network packet (e.g., a data packet and/or the like) that includes data.

As used herein, the term "if" is, optionally, construed to mean "when", "upon", "in response to determining," "in response to detecting," and/or the like, depending on the context. Similarly, the phrase "if it is determined" or "if [a stated condition or event] is detected" is, optionally, construed to mean "upon determining," "in response to determining," "upon detecting [the stated condition or event]," "in response to detecting [the stated condition or event]," and/or the like, depending on the context. Also, as used herein, the terms "has", "have", "having", or the like are intended to be open-ended terms. Further, the phrase "based on" is intended to mean "based at least partially on" unless explicitly stated otherwise.

Reference will now be made in detail to embodiments, examples of which are illustrated in the accompanying drawings. In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the various described embodiments. However, it will be apparent to one of ordinary skill in the art that the various described embodiments can be practiced without these specific details. In other instances, well-known methods, procedures, components, circuits, and networks have not been described in detail so as not to unnecessarily obscure aspects of the embodiments.

General Overview

In some aspects and/or embodiments, systems, methods, and computer program products described herein include and/or implement aligning a raster map with a geodata map to maximize the coverage of the geodata map over the raster map. A geodata map may include graph-based geographic data in which the edges (e.g., undirected edges) of the graph represent traffic lanes and the nodes of the graph represent intersections between two or more traffic lanes. A raster map may include a matrix of pixels in which the physical features present in a geographic area are represented by one or more of the pixels. To maximize coverage of a geodata map over a corresponding raster map, the geodata map may undergo a non-rigid transformation in which the graph network of the geodata map is deformed. The accuracy and consistency of downstream tasks, such as annotation, navigation, and localization, may be increased by using the updated geodata map. For example, sematic annotations in which one or more sematic labels are assigned to various physical features present in a geographic area may be performed based on a geodata map updated through the non-rigid transformation. The updated geodata map may also be used to generate a basemap for the geographic area, which is a reference map upon which to overlay one or more layers of spatial data, such as roads, buildings, habitat types, and administrative boundaries.

By virtue of the implementation of systems, methods, and computer program products described herein, techniques for aligning a geodata map with a corresponding raster map may be provided. In some instances, the geodata map (e.g., the graph-based geographic data) may not be metrically consistent, which may prevent the geodata map from being aligned with the corresponding raster map such that the physical features present in the raster map coincide maximally with the corresponding nodes and edges in the geodata map. An improper alignment between the geodata map and the raster map may result in the incorrect localization of physical features present in the geographic area. As such, an improper alignment between the geodata map and the raster map may diminish the ability of an autonomous vehicle to navigate its surroundings.

As discussed in more detail below, the present disclosure relates to an improvement in aligning a geodata map with a corresponding raster map. In some embodiments, alignment between the geodata map and the raster map may be improved by subjecting the geodata map to a non-rigid transformation in which one or more nodes and edges in the geodata map are deformed to maximize a coverage of the geodata map over the raster map. For example, the geodata map may be deformed to minimize an error function determined based on a factor graph of the geodata map. The deforming of the geodata map may include moving one or more nodes of the geodata map to minimize a range error corresponding to a distance between the one or more nodes of the geodata map and one or more peaks in a distance map in which each pixel of the rater map is labeled with a distance from a closest obstacle. The moving of the one or more nodes may deform one or more corresponding edges in the geodata map. Moreover, the deforming of the geodata map may include moving the one or more edges of the geodata map to minimize a coverage error corresponding to an offset between the one or more edges and one or more areas of local maxima on the distance map. Performing downstream tasks, such as annotation, navigation, and localization, based on the updated geodata map may increase the accuracy and consistency of these tasks.

The term "sensor data," as used herein, refers to data generated by or generally derivable from sensors (e.g., sensors from an autonomous system that is the same as or similar to autonomous system **202**, described below) that reflect the physical world. For example, sensor data may refer to raw data (e.g., the bits generated by a sensor) or to data points, images, point cloud, electronic map data of a geographic area, etc., generated from such raw data. As an illustrative example, sensor data may refer to a "ground-level" or "street-level" image, such as an image directly captured by a camera, a point cloud generated from a LiDAR sensor, a "birds-eye view" (e.g., top-view) image or map generated by movement of a sensor through a geographic area, or the like. In some instances, the raster map described herein may be derived at least in part from sensor data. Moreover, semantic annotations may be used to modify such images in a manner that identifies features of the images.

The term "geographic data," as used herein, refers to graph-based geographic data (sometimes referred to as geospatial data, georeferenced data, geoinformation, or geodata) in which traffic lanes are represented as edges (e.g., undirected edges) and intersections between traffic lanes are represented as nodes. Examples of geographic data include OpenStreetMap (OSM) project data, Google Maps data, HERE map data, or the like. The geodata map described herein may be derived at least in part from geographic data.

Referring now to FIG. **1**, illustrated is example environment **100** in which vehicles that include autonomous systems, as well as vehicles that do not, are operated. As illustrated, environment **100** includes vehicles **102***a*-**102***n*, objects **104***a*-**104***n*, routes **106***a*-**106***n*, area **108**, vehicle-to-infrastructure (V2I) device **110**, network **112**, remote autonomous vehicle (AV) system **114**, fleet management system **116**, and V2I system **118**. Vehicles **102***a*-**102***n*, vehicle-to-infrastructure (V2I) device **110**, network **112**, autonomous vehicle (AV) system **114**, fleet management system **116**, and V2I system **118** interconnect (e.g., establish a connection to communicate and/or the like) via wired connections, wireless connections, or a combination of wired or wireless connections. In some embodiments, objects **104***a*-**104***n* interconnect with at least one of vehicles **102***a*-**102***n*, vehicle-to-infrastructure (V2I) device **110**, network **112**, autonomous vehicle (AV) system **114**, fleet management system **116**, and V2I system **118** via wired connections, wireless connections, or a combination of wired or wireless connections.

Vehicles **102***a*-**102***n* (referred to individually as vehicle **102** and collectively as vehicles **102**) include at least one device configured to transport goods and/or people. In some embodiments, vehicles **102** are configured to be in communication with V2I device **110**, remote AV system **114**, fleet management system **116**, and/or V2I system **118** via network **112**. In some embodiments, vehicles **102** include cars, buses, trucks, trains, and/or the like. In some embodiments, vehicles **102** are the same as, or similar to, vehicles **200**, described herein (see FIG. **2**). In some embodiments, a vehicle **200** of a set of vehicles **200** is associated with an autonomous fleet manager. In some embodiments, vehicles **102** travel along respective routes **106***a*-**106***n* (referred to individually as route **106** and collectively as routes **106**), as described herein. In some embodiments, one or more vehicles **102** include an autonomous system (e.g., an autonomous system that is the same as or similar to autonomous system **202**).

Objects **104***a*-**104***n* (referred to individually as object **104** and collectively as objects **104**) include, for example, at least one vehicle, at least one pedestrian, at least one cyclist, at least one structure (e.g., a building, a sign, a fire hydrant, etc.), and/or the like. Each object **104** is stationary (e.g., located at a fixed location for a period of time) or mobile (e.g., having a velocity and associated with at least one trajectory). In some embodiments, objects **104** are associated with corresponding locations in area **108**.

Routes **106***a*-**106***n* (referred to individually as route **106** and collectively as routes **106**) are each associated with (e.g., prescribe) a sequence of actions (also known as a trajectory) connecting states along which an AV can navigate. Each route **106** starts at an initial state (e.g., a state that corresponds to a first spatiotemporal location, velocity, and/or the like) and a final goal state (e.g., a state that corresponds to a second spatiotemporal location that is different from the first spatiotemporal location) or goal region (e.g. a subspace of acceptable states (e.g., terminal states)). In some embodiments, the first state includes a location at which an individual or individuals are to be picked-up by the AV and the second state or region includes a location or locations at which the individual or individuals picked-up by the AV are to be dropped-off. In some embodiments, routes **106** include a plurality of acceptable state sequences (e.g., a plurality of spatiotemporal location sequences), the plurality of state sequences associated with (e.g., defining) a plurality of trajectories. In an example, routes **106** include only high level actions or imprecise state locations, such as a series of connected roads dictating turning directions at roadway intersections. Additionally, or alternatively, routes **106** may include more precise actions or states such as, for example, specific target lanes or precise locations within the lane areas and targeted speed at those positions. In an example, routes **106** include a plurality of precise state sequences along the at least one high level action sequence with a limited lookahead horizon to reach intermediate goals, where the combination of successive iterations of limited horizon state sequences cumulatively correspond to a plurality of trajectories that collectively form the high level route to terminate at the final goal state or region.

Area **108** includes a physical area (e.g., a geographic region) within which vehicles **102** can navigate. In an example, area **108** includes at least one state (e.g., a country, a province, an individual state of a plurality of states included in a country, etc.), at least one portion of a state, at least one city, at least one portion of a city, etc. In some embodiments, area **108** includes at least one named thoroughfare (referred to herein as a "road") such as a highway, an interstate highway, a parkway, a city street, etc. Additionally, or alternatively, in some examples area **108** includes at least one unnamed road such as a driveway, a section of a parking lot, a section of a vacant and/or undeveloped lot, a dirt path, etc. In some embodiments, a road includes at least one lane (e.g., a portion of the road that can be traversed by vehicles **102**). In an example, a road includes at least one lane associated with (e.g., identified based on) at least one lane marking.

Vehicle-to-Infrastructure (V2I) device **110** (sometimes referred to as a Vehicle-to-Infrastructure (V2X) device) includes at least one device configured to be in communication with vehicles **102** and/or V2I infrastructure system **118**. In some embodiments, V2I device **110** is configured to be in communication with vehicles **102**, remote AV system **114**, fleet management system **116**, and/or V2I system **118** via network **112**. In some embodiments, V2I device **110** includes a radio frequency identification (RFID) device, signage, cameras (e.g., two-dimensional (2D) and/or three-dimensional (3D) cameras), lane markers, streetlights, parking meters, etc. In some embodiments, V2I device **110** is configured to communicate directly with vehicles **102**. Additionally, or alternatively, in some embodiments V2I device **110** is configured to communicate with vehicles **102**, remote AV system **114**, and/or fleet management system **116** via V2I system **118**. In some embodiments, V2I device **110** is configured to communicate with V2I system **118** via network **112**.

Network **112** includes one or more wired and/or wireless networks. In an example, network **112** includes a cellular network (e.g., a long term evolution (LTE) network, a third generation (3G) network, a fourth generation (4G) network, a fifth generation (5G) network, a code division multiple access (CDMA) network, etc.), a public land mobile network (PLMN), a local area network (LAN), a wide area network (WAN), a metropolitan area network (MAN), a telephone network (e.g., the public switched telephone network (PSTN), a private network, an ad hoc network, an intranet, the Internet, a fiber optic-based network, a cloud computing network, etc., a combination of some or all of these networks, and/or the like.

Remote AV system **114** includes at least one device configured to be in communication with vehicles **102**, V2I device **110**, network **112**, remote AV system **114**, fleet management system **116**, and/or V2I system **118** via network **112**. In an example, remote AV system **114** includes a server, a group of servers, and/or other like devices. In some embodiments, remote AV system **114** is co-located with the fleet management system **116**. In some embodiments, remote AV system **114** is involved in the installation of some or all of the components of a vehicle, including an autonomous system, an autonomous vehicle compute, software implemented by an autonomous vehicle compute, and/or the like. In some embodiments, remote AV system **114** maintains (e.g., updates and/or replaces) such components and/or software during the lifetime of the vehicle.

Fleet management system **116** includes at least one device configured to be in communication with vehicles **102**, V2I device **110**, remote AV system **114**, and/or V2I infrastructure system **118**. In an example, fleet management system **116** includes a server, a group of servers, and/or other like devices. In some embodiments, fleet management system **116** is associated with a ridesharing company (e.g., an organization that controls operation of multiple vehicles (e.g., vehicles that include autonomous systems and/or vehicles that do not include autonomous systems) and/or the like).

In some embodiments, V2I system **118** includes at least one device configured to be in communication with vehicles **102**, V2I device **110**, remote AV system **114**, and/or fleet management system **116** via network **112**. In some examples, V2I system **118** is configured to be in communication with V2I device **110** via a connection different from network **112**. In some embodiments, V2I system **118** includes a server, a group of servers, and/or other like devices. In some embodiments, V2I system **118** is associated with a municipality or a private institution (e.g., a private institution that maintains V2I device **110** and/or the like).

The number and arrangement of elements illustrated in FIG. **1** are provided as an example. There can be additional elements, fewer elements, different elements, and/or differently arranged elements, than those illustrated in FIG. **1**. Additionally, or alternatively, at least one element of environment **100** can perform one or more functions described as being performed by at least one different element of FIG. **1**. Additionally, or alternatively, at least one set of elements of environment **100** can perform one or more functions described as being performed by at least one different set of elements of environment **100**.

Referring now to FIG. **2**, vehicle **200** includes autonomous system **202**, powertrain control system **204**, steering control system **206**, and brake system **208**. In some embodiments, vehicle **200** is the same as or similar to vehicle **102** (see FIG. **1**). In some embodiments, vehicle **102** have autonomous capability (e.g., implement at least one function, feature, device, and/or the like that enable vehicle **200** to be partially or fully operated without human intervention including, without limitation, fully autonomous vehicles (e.g., vehicles that forego reliance on human intervention), highly autonomous vehicles (e.g., vehicles that forego reliance on human intervention in certain situations), and/or the like). For a detailed description of fully autonomous vehicles and highly autonomous vehicles, reference may be made to SAE International's standard J3016: Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems, which is incorporated by reference in its entirety. In some embodiments, vehicle **200** is associated with an autonomous fleet manager and/or a ridesharing company.

Autonomous system **202** includes a sensor suite that includes one or more devices such as cameras **202***a*, LiDAR sensors **202***b*, radar sensors **202***c*, and microphones **202***d*. In some embodiments, autonomous system **202** can include more or fewer devices and/or different devices (e.g., ultrasonic sensors, inertial sensors, GPS receivers (discussed below), odometry sensors that generate data associated with an indication of a distance that vehicle **200** has traveled, and/or the like). In some embodiments, autonomous system **202** uses the one or more devices included in autonomous system **202** to generate data associated with environment **100**, described herein. The data generated by the one or more devices of autonomous system **202** can be used by one or more systems described herein to observe the environment (e.g., environment **100**) in which vehicle **200** is located. In some embodiments, autonomous system **202** includes communication device **202***e*, autonomous vehicle compute **202***f*, and drive-by-wire (DBW) system **202***h*.

Cameras **202***a* include at least one device configured to be in communication with communication device **202***e*, autonomous vehicle compute **202***f*, and/or safety controller **202***g* via a bus (e.g., a bus that is the same as or similar to bus **302** of FIG. **3**). Cameras **202***a* include at least one camera (e.g., a digital camera using a light sensor such as a charge-coupled device (CCD), a thermal camera, an infrared (IR) camera, an event camera, and/or the like) to capture images including physical objects (e.g., cars, buses, curbs, people, and/or the like). In some embodiments, camera **202***a* generates camera data as output. In some examples, camera **202***a* generates camera data that includes image data associated with an image. In this example, the image data may specify at least one parameter (e.g., image characteristics such as exposure, brightness, etc., an image timestamp, and/or the like) corresponding to the image. In such an example, the image may be in a format (e.g., RAW, JPEG, PNG, and/or the like). In some embodiments, camera **202***a* includes a plurality of independent cameras configured on (e.g., positioned on) a vehicle to capture images for the purpose of stereopsis (stereo vision). In some examples, camera **202***a* includes a plurality of cameras that generate image data and transmit the image data to autonomous vehicle compute **202***f* and/or a fleet management system (e.g., a fleet management system that is the same as or similar to fleet management system **116** of FIG. **1**). In such an example, autonomous vehicle compute **202***f* determines depth to one or more objects in a field of view of at least two cameras of the plurality of cameras based on the image data from the at least two cameras. In some embodiments, cameras **202***a* is configured to capture images of objects within a distance from cameras **202***a* (e.g., up to 100 meters, up to a kilometer, and/or the like). Accordingly, cameras **202***a* include features such as sensors and lenses that are optimized for perceiving objects that are at one or more distances from cameras **202***a*.

In an embodiment, camera **202***a* includes at least one camera configured to capture one or more images associated with one or more traffic lights, street signs and/or other physical objects that provide visual navigation information. In some embodiments, camera **202***a* generates traffic light data associated with one or more images. In some examples, camera **202***a* generates TLD data associated with one or more images that include a format (e.g., RAW, JPEG, PNG, and/or the like). In some embodiments, camera **202***a* that generates TLD data differs from other systems described herein incorporating cameras in that camera **202***a* can include one or more cameras with a wide field of view (e.g., a wide-angle lens, a fish-eye lens, a lens having a viewing angle of approximately 120 degrees or more, and/or the like) to generate images about as many physical objects as possible.

Laser Detection and Ranging (LiDAR) sensors **202***b* include at least one device configured to be in communication with communication device **202***e*, autonomous vehicle compute **202***f*, and/or safety controller **202***g* via a bus (e.g., a bus that is the same as or similar to bus **302** of FIG. **3**). LiDAR sensors **202***b* include a system configured to transmit light from a light emitter (e.g., a laser transmitter). Light emitted by LiDAR sensors **202***b* include light (e.g., infrared light and/or the like) that is outside of the visible spectrum. In some embodiments, during operation, light emitted by LiDAR sensors **202***b* encounters a physical object (e.g., a vehicle) and is reflected back to LiDAR sensors **202***b*. In some embodiments, the light emitted by LiDAR sensors **202***b* does not penetrate the physical objects that the light encounters. LiDAR sensors **202***b* also include at least one light detector which detects the light that was emitted from the light emitter after the light encounters a physical object. In some embodiments, at least one data processing system associated with LiDAR sensors **202***b* generates an image (e.g., a point cloud, a combined point cloud, and/or the like) representing the objects included in a field of view of LiDAR sensors **202***b*. In some examples, the at least one data processing system associated with LiDAR sensor **202***b* generates an image that represents the boundaries of a physical object, the surfaces (e.g., the topology of the surfaces) of the physical object, and/or the like. In such an example, the image is used to determine the boundaries of physical objects in the field of view of LiDAR sensors **202***b*.

Radio Detection and Ranging (radar) sensors **202***c* include at least one device configured to be in communication with communication device **202***e*, autonomous vehicle compute **202***f*, and/or safety controller **202***g* via a bus (e.g., a bus that is the same as or similar to bus **302** of FIG. **3**). Radar sensors **202***c* include a system configured to transmit radio waves (either pulsed or continuously). The radio waves transmitted by radar sensors **202***c* include radio waves that are within a predetermined spectrum In some embodiments, during operation, radio waves transmitted by radar sensors **202***c* encounter a physical object and are reflected back to radar sensors **202***c*. In some embodiments, the radio waves transmitted by radar sensors **202***c* are not reflected by some objects. In some embodiments, at least one data processing system associated with radar sensors **202***c* generates signals representing the objects included in a field of view of radar sensors **202***c*. For example, the at least one data processing system associated with radar sensor **202***c* generates an image that represents the boundaries of a physical object, the surfaces (e.g., the topology of the surfaces) of the physical object, and/or the like. In some examples, the image is used to determine the boundaries of physical objects in the field of view of radar sensors **202***c*.

Microphones **202***d* includes at least one device configured to be in communication with communication device **202***e*, autonomous vehicle compute **202***f*, and/or safety controller **202***g* via a bus (e.g., a bus that is the same as or similar to bus **302** of FIG. **3**). Microphones **202***d* include one or more microphones (e.g., array microphones, external microphones, and/or the like) that capture audio signals and generate data associated with (e.g., representing) the audio signals. In some examples, microphones **202***d* include transducer devices and/or like devices. In some embodiments, one or more systems described herein can receive the data generated by microphones **202***d* and determine a position of an object relative to vehicle **200** (e.g., a distance and/or the like) based on the audio signals associated with the data.

Communication device **202***e* include at least one device configured to be in communication with cameras **202***a*, LiDAR sensors **202***b*, radar sensors **202***c*, microphones **202***d*, autonomous vehicle compute **202***f*, safety controller **202***g*, and/or DBW system **202***h*. For example, communication device **202***e* may include a device that is the same as or similar to communication interface **314** of FIG. **3**. In some embodiments, communication device **202***e* includes a vehicle-to-vehicle (V2V) communication device (e.g., a device that enables wireless communication of data between vehicles).

Autonomous vehicle compute **202***f* include at least one device configured to be in communication with cameras **202***a*, LiDAR sensors **202***b*, radar sensors **202***c*, microphones **202***d*, communication device **202***e*, safety controller **202***g*, and/or DBW system **202***h*. In some examples, autonomous vehicle compute **202***f* includes a device such as a client device, a mobile device (e.g., a cellular telephone, a tablet, and/or the like) a server (e.g., a computing device including one or more central processing units, graphical processing units, and/or the like), and/or the like. In some embodiments, autonomous vehicle compute **202***f* is the same as or similar to autonomous vehicle compute **400**, described herein. Additionally, or alternatively, in some embodiments autonomous vehicle compute **202***f* is configured to be in communication with an autonomous vehicle system (e.g., an autonomous vehicle system that is the same as or similar to remote AV system **114** of FIG. **1**), a fleet management system (e.g., a fleet management system that is the same as or similar to fleet management system **116** of FIG. **1**), a V2I device (e.g., a V2I device that is the same as or similar to V2I device **110** of FIG. **1**), and/or a V2I system (e.g., a V2I system that is the same as or similar to V2I system **118** of FIG. **1**).

Safety controller **202***g* includes at least one device configured to be in communication with cameras **202***a*, LiDAR sensors **202***b*, radar sensors **202***c*, microphones **202***d*, communication device **202***e*, autonomous vehicle computer **202***f*, and/or DBW system **202***h*. In some examples, safety controller **202***g* includes one or more controllers (electrical controllers, electromechanical controllers, and/or the like) that are configured to generate and/or transmit control signals to operate one or more devices of vehicle **200** (e.g., powertrain control system **204**, steering control system **206**, brake system **208**, and/or the like). In some embodiments, safety controller **202***g* is configured to generate control signals that take precedence over (e.g., overrides) control signals generated and/or transmitted by autonomous vehicle compute **202***f*.

DBW system **202***h* includes at least one device configured to be in communication with communication device **202***e* and/or autonomous vehicle compute **202***f*. In some examples, DBW system **202***h* includes one or more controllers (e.g., electrical controllers, electromechanical controllers, and/or the like) that are configured to generate and/or transmit control signals to operate one or more devices of vehicle **200** (e.g., powertrain control system **204**, steering control system **206**, brake system **208**, and/or the like). Additionally, or alternatively, the one or more controllers of

DBW system **202***h* are configured to generate and/or transmit control signals to operate at least one different device (e.g., a turn signal, headlights, door locks, windshield wipers, and/or the like) of vehicle **200**.

Powertrain control system **204** includes at least one device configured to be in communication with DBW system **202***h*. In some examples, powertrain control system **204** includes at least one controller, actuator, and/or the like. In some embodiments, powertrain control system **204** receives control signals from DBW system **202***h* and powertrain control system **204** causes vehicle **200** to start moving forward, stop moving forward, start moving backward, stop moving backward, accelerate in a direction, decelerate in a direction, perform a left turn, perform a right turn, and/or the like. In an example, powertrain control system **204** causes the energy (e.g., fuel, electricity, and/or the like) provided to a motor of the vehicle to increase, remain the same, or decrease, thereby causing at least one wheel of vehicle **200** to rotate or not rotate.

Steering control system **206** includes at least one device configured to rotate one or more wheels of vehicle **200**. In some examples, steering control system **206** includes at least one controller, actuator, and/or the like. In some embodiments, steering control system **206** causes the front two wheels and/or the rear two wheels of vehicle **200** to rotate to the left or right to cause vehicle **200** to turn to the left or right.

Brake system **208** includes at least one device configured to actuate one or more brakes to cause vehicle **200** to reduce speed and/or remain stationary. In some examples, brake system **208** includes at least one controller and/or actuator that is configured to cause one or more calipers associated with one or more wheels of vehicle **200** to close on a corresponding rotor of vehicle **200**. Additionally, or alternatively, in some examples brake system **208** includes an automatic emergency braking (AEB) system, a regenerative braking system, and/or the like.

In some embodiments, vehicle **200** includes at least one platform sensor (not explicitly illustrated) that measures or infers properties of a state or a condition of vehicle **200**. In some examples, vehicle **200** includes platform sensors such as a global positioning system (GPS) receiver, an inertial measurement unit (IMU), a wheel speed sensor, a wheel brake pressure sensor, a wheel torque sensor, an engine torque sensor, a steering angle sensor, and/or the like.

Referring now to FIG. **3**, illustrated is a schematic diagram of a device **300**. As illustrated, device **300** includes processor **304**, memory **306**, storage component **308**, input interface **310**, output interface **312**, communication interface **314**, and bus **302**. In some embodiments, device **300** corresponds to at least one device of vehicles **102** (e.g., at least one device of a system of vehicles **102**), at least one device of vehicle-to-infrastructure (V2I) device **110**, and/or one or more devices of network **112** (e.g., one or more devices of a system of network **112**). In some embodiments, one or more devices of vehicles **102** (e.g., one or more devices of a system of vehicles **102**), and/or one or more devices of network **112** (e.g., one or more devices of a system of network **112**) include at least one device **300** and/or at least one component of device **300**. As shown in FIG. **3**, device **300** includes bus **302**, processor **304**, memory **306**, storage component **308**, input interface **310**, output interface **312**, and communication interface **314**.

Bus **302** includes a component that permits communication among the components of device **300**. In some embodiments, processor **304** is implemented in hardware, software, or a combination of hardware and software. In some examples, processor **304** includes a processor (e.g., a central processing unit (CPU), a graphics processing unit (GPU), an accelerated processing unit (APU), and/or the like), a microphone, a digital signal processor (DSP), and/or any processing component (e.g., a field-programmable gate array (FPGA), an application specific integrated circuit (ASIC), and/or the like) that can be programmed to perform at least one function. Memory **306** includes random access memory (RAM), read-only memory (ROM), and/or another type of dynamic and/or static storage device (e.g., flash memory, magnetic memory, optical memory, and/or the like) that stores data and/or instructions for use by processor **304**.

Storage component **308** stores data and/or software related to the operation and use of device **300**. In some examples, storage component **308** includes a hard disk (e.g., a magnetic disk, an optical disk, a magneto-optic disk, a solid state disk, and/or the like), a compact disc (CD), a digital versatile disc (DVD), a floppy disk, a cartridge, a magnetic tape, a CD-ROM, RAM, PROM, EPROM, FLASH-EPROM, NV-RAM, and/or another type of computer readable medium, along with a corresponding drive.

Input interface **310** includes a component that permits device **300** to receive information, such as via user input (e.g., a touchscreen display, a keyboard, a keypad, a mouse, a button, a switch, a microphone, a camera, and/or the like). Additionally or alternatively, in some embodiments input interface **310** includes a sensor that senses information (e.g., a global positioning system (GPS) receiver, an accelerometer, a gyroscope, an actuator, and/or the like). Output interface **312** includes a component that provides output information from device **300** (e.g., a display, a speaker, one or more light-emitting diodes (LEDs), and/or the like).

In some embodiments, communication interface **314** includes a transceiver-like component (e.g., a transceiver, a separate receiver and transmitter, and/or the like) that permits device **300** to communicate with other devices via a wired connection, a wireless connection, or a combination of wired and wireless connections. In some examples, communication interface **314** permits device **300** to receive information from another device and/or provide information to another device. In some examples, communication interface **314** includes an Ethernet interface, an optical interface, a coaxial interface, an infrared interface, a radio frequency (RF) interface, a universal serial bus (USB) interface, a Wi-Fi® interface, a cellular network interface, and/or the like.

In some embodiments, device **300** performs one or more processes described herein. Device **300** performs these processes based on processor **304** executing software instructions stored by a computer-readable medium, such as memory **305** and/or storage component **308**. A computer-readable medium (e.g., a non-transitory computer readable medium) is defined herein as a non-transitory memory device. A non-transitory memory device includes memory space located inside a single physical storage device or memory space spread across multiple physical storage devices.

In some embodiments, software instructions are read into memory **306** and/or storage component **308** from another computer-readable medium or from another device via communication interface **314**. When executed, software instructions stored in memory **306** and/or storage component **308** cause processor **304** to perform one or more processes described herein. Additionally or alternatively, hardwired circuitry is used in place of or in combination with software instructions to perform one or more processes described herein. Thus, embodiments described herein are not limited to any specific combination of hardware circuitry and software unless explicitly stated otherwise.

Memory **306** and/or storage component **308** includes data storage or at least one data structure (e.g., a database and/or the like). Device **300** is capable of receiving information from, storing information in, communicating information to, or searching information stored in the data storage or the at least one data structure in memory **306** or storage component **308**. In some examples, the information includes network data, input data, output data, or any combination thereof.

In some embodiments, device **300** is configured to execute software instructions that are either stored in memory **306** and/or in the memory of another device (e.g., another device that is the same as or similar to device **300**). As used herein, the term "module" refers to at least one instruction stored in memory **306** and/or in the memory of another device that, when executed by processor **304** and/or by a processor of another device (e.g., another device that is the same as or similar to device **300**) cause device **300** (e.g., at least one component of device **300**) to perform one or more processes described herein. In some embodiments, a module is implemented in software, firmware, hardware, and/or the like.

The number and arrangement of components illustrated in FIG. **3** are provided as an example. In some embodiments, device **300** can include additional components, fewer components, different components, or differently arranged components than those illustrated in FIG. **3**. Additionally or alternatively, a set of components (e.g., one or more components) of device **300** can perform one or more functions described as being performed by another component or another set of components of device **300**.

Referring now to FIG. **4**, illustrated is an example block diagram of an autonomous vehicle compute **400** (sometimes referred to as an "AV stack"). As illustrated, autonomous vehicle compute **400** includes perception system **402** (sometimes referred to as a perception module), planning system **404** (sometimes referred to as a planning module), localization system **406** (sometimes referred to as a localization module), control system **408** (sometimes referred to as a control module), and database **410**. In some embodiments, perception system **402**, planning system **404**, localization system **406**, control system **408**, and database **410** are included and/or implemented in an autonomous navigation system of a vehicle (e.g., autonomous vehicle compute **202*f*** of vehicle **200**). Additionally, or alternatively, in some embodiments perception system **402**, planning system **404**, localization system **406**, control system **408**, and database **410** are included in one or more standalone systems (e.g., one or more systems that are the same as or similar to autonomous vehicle compute **400** and/or the like). In some examples, perception system **402**, planning system **404**, localization system **406**, control system **408**, and database **410** are included in one or more standalone systems that are located in a vehicle and/or at least one remote system as described herein. In some embodiments, any and/or all of the systems included in autonomous vehicle compute **400** are implemented in software (e.g., in software instructions stored in memory), computer hardware (e.g., by microprocessors, microcontrollers, application-specific integrated circuits [ASICs], Field Programmable Gate Arrays (FPGAs), and/or the like), or combinations of computer software and computer hardware. It will also be understood that, in some embodiments, autonomous vehicle compute **400** is configured to be in communication with a remote system (e.g., an autonomous vehicle system that is the same as or similar to remote AV system **114**, a fleet management system **116** that is the same as or similar to fleet management system **116**, a V2I system that is the same as or similar to V2I system **118**, and/or the like).

In some embodiments, perception system **402** receives data associated with at least one physical object (e.g., data that is used by perception system **402** to detect the at least one physical object) in an environment and classifies the at least one physical object. In some examples, perception system **402** receives image data captured by at least one camera (e.g., cameras **202*a***), the image associated with (e.g., representing) one or more physical objects within a field of view of the at least one camera. In such an example, perception system **402** classifies at least one physical object based on one or more groupings of physical objects (e.g., bicycles, vehicles, traffic signs, pedestrians, and/or the like). In some embodiments, perception system **402** transmits data associated with the classification of the physical objects to planning system **404** based on perception system **402** classifying the physical objects.

In some embodiments, planning system **404** receives data associated with a destination and generates data associated with at least one route (e.g., routes **106**) along which a vehicle (e.g., vehicles **102**) can travel along toward a destination. In some embodiments, planning system **404** periodically or continuously receives data from perception system **402** (e.g., data associated with the classification of physical objects, described above) and planning system **404** updates the at least one trajectory or generates at least one different trajectory based on the data generated by perception system **402**. In some embodiments, planning system **404** receives data associated with an updated position of a vehicle (e.g., vehicles **102**) from localization system **406** and planning system **404** updates the at least one trajectory or generates at least one different trajectory based on the data generated by localization system **406**.

In some embodiments, localization system **406** receives data associated with (e.g., representing) a location of a vehicle (e.g., vehicles **102**) in an area. In some examples, localization system **406** receives LiDAR data associated with at least one point cloud generated by at least one LiDAR sensor (e.g., LiDAR sensors **202*b***). In certain examples, localization system **406** receives data associated with at least one point cloud from multiple LiDAR sensors and localization system **406** generates a combined point cloud based on each of the point clouds. In these examples, localization system **406** compares the at least one point cloud or the combined point cloud to two-dimensional (2D) and/or a three-dimensional (3D) map of the area stored in database **410**. Localization system **406** then determines the position of the vehicle in the area based on localization system **406** comparing the at least one point cloud or the combined point cloud to the map. In some embodiments, the map includes a combined point cloud of the area generated prior to navigation of the vehicle. In some embodiments, maps include, without limitation, high-precision maps of the roadway geometric properties, maps describing road network connectivity properties, maps describing roadway physical properties (such as traffic speed, traffic volume, the number of vehicular and cyclist traffic lanes, lane width, lane traffic directions, or lane marker types and locations, or combinations thereof), and maps describing the spatial locations of road features such as crosswalks, traffic signs or other travel signals of various types. In some embodiments, the map is generated in real-time based on the data received by the perception system.

In another example, localization system **406** receives Global Navigation Satellite System (GNSS) data generated by a global positioning system (GPS) receiver. In some examples, localization system **406** receives GNSS data associated with the location of the vehicle in the area and localization system **406** determines a latitude and longitude of the vehicle in the area. In such an example, localization system **406** determines the position of the vehicle in the area based on the latitude and longitude of the vehicle. In some embodiments, localization system **406** generates data associated with the position of the vehicle. In some examples, localization system **406** generates data associated with the position of the vehicle based on localization system **406** determining the position of the vehicle. In such an example, the data associated with the position of the vehicle includes data associated with one or more semantic properties corresponding to the position of the vehicle.

In some embodiments, control system **408** receives data associated with at least one trajectory from planning system **404** and control system **408** controls operation of the vehicle. In some examples, control system **408** receives data associated with at least one trajectory from planning system **404** and control system **408** controls operation of the vehicle by generating and transmitting control signals to cause a powertrain control system (e.g., DBW system **202***h*, powertrain control system **204**, and/or the like), a steering control system (e.g., steering control system **206**), and/or a brake system (e.g., brake system **208**) to operate. In an example, where a trajectory includes a left turn, control system **408** transmits a control signal to cause steering control system **206** to adjust a steering angle of vehicle **200**, thereby causing vehicle **200** to turn left. Additionally, or alternatively, control system **408** generates and transmits control signals to cause other devices (e.g., headlights, turn signal, door locks, windshield wipers, and/or the like) of vehicle **200** to change states.

In some embodiments, perception system **402**, planning system **404**, localization system **406**, and/or control system **408** implement at least one machine learning model (e.g., at least one multilayer perceptron (MLP), at least one convolutional neural network (CNN), at least one recurrent neural network (RNN), at least one autoencoder, at least one transformer, and/or the like). In some examples, perception system **402**, planning system **404**, localization system **406**, and/or control system **408** implement at least one machine learning model alone or in combination with one or more of the above-noted systems. In some examples, perception system **402**, planning system **404**, localization system **406**, and/or control system **408** implement at least one machine learning model as part of a pipeline (e.g., a pipeline for identifying one or more objects located in an environment and/or the like). An example of an implementation of a machine learning model is included below with respect to FIGS. **4**B-**4**D.

Database **410** stores data that is transmitted to, received from, and/or updated by perception system **402**, planning system **404**, localization system **406** and/or control system **408**. In some examples, database **410** includes a storage component (e.g., a storage component that is the same as or similar to storage component **308** of FIG. **3**) that stores data and/or software related to the operation and uses at least one system of autonomous vehicle compute **400**. In some embodiments, database **410** stores data associated with 2D and/or 3D maps of at least one area. In some examples, database **410** stores data associated with 2D and/or 3D maps of a portion of a city, multiple portions of multiple cities, multiple cities, a county, a state, a State (e.g., a country), and/or the like). In such an example, a vehicle (e.g., a vehicle that is the same as or similar to vehicles **102** and/or vehicle **200**) can drive along one or more drivable regions (e.g., single-lane roads, multi-lane roads, highways, back roads, off road trails, and/or the like) and cause at least one LiDAR sensor (e.g., a LIDAR sensor that is the same as or similar to LiDAR sensors **202***b*) to generate data associated with an image representing the objects included in a field of view of the at least one LiDAR sensor.

In some embodiments, database **410** can be implemented across a plurality of devices. In some examples, database **410** is included in a vehicle (e.g., a vehicle that is the same as or similar to vehicles **102** and/or vehicle **200**), an autonomous vehicle system (e.g., an autonomous vehicle system that is the same as or similar to remote AV system **114**, a fleet management system (e.g., a fleet management system that is the same as or similar to fleet management system **116** of FIG. **1**, a V2I system (e.g., a V2I system that is the same as or similar to V2I system **118** of FIG. **1**) and/or the like.

Referring now to FIG. **4**B, illustrated is a diagram of an implementation of a machine learning model. More specifically, illustrated is a diagram of an implementation of a convolutional neural network (CNN) **420**. For purposes of illustration, the following description of CNN **420** will be with respect to an implementation of CNN **420** by perception system **402**. However, it will be understood that in some examples CNN **420** (e.g., one or more components of CNN **420**) is implemented by other systems different from, or in addition to, perception system **402** such as planning system **404**, localization system **406**, and/or control system **408**. While CNN **420** includes certain features as described herein, these features are provided for the purpose of illustration and are not intended to limit the present disclosure.

CNN **420** includes a plurality of convolution layers including first convolution layer **422**, second convolution layer **424**, and convolution layer **426**. In some embodiments, CNN **420** includes sub-sampling layer **428** (sometimes referred to as a pooling layer). In some embodiments, sub-sampling layer **428** and/or other subsampling layers have a dimension (i.e., an amount of nodes) that is less than a dimension of an upstream system. By virtue of sub-sampling layer **428** having a dimension that is less than a dimension of an upstream layer, CNN **420** consolidates the amount of data associated with the initial input and/or the output of an upstream layer to thereby decrease the amount of computations necessary for CNN **420** to perform downstream convolution operations. Additionally, or alternatively, by virtue of sub-sampling layer **428** being associated with (e.g., configured to perform) at least one subsampling function (as described below with respect to FIGS. **4**C and **4**D), CNN **420** consolidates the amount of data associated with the initial input.

Perception system **402** performs convolution operations based on perception system **402** providing respective inputs and/or outputs associated with each of first convolution layer **422**, second convolution layer **424**, and convolution layer **426** to generate respective outputs. In some examples, perception system **402** implements CNN **420** based on perception system **402** providing data as input to first convolution layer **422**, second convolution layer **424**, and convolution layer **426**. In such an example, perception system **402** provides the data as input to first convolution layer **422**, second convolution layer **424**, and convolution layer **426** based on perception system **402** receiving data from one or more different systems (e.g., one or more systems of a vehicle that is the same as or similar to vehicle **102**), a remote AV system that is the same as or similar to remote AV system **114**, a fleet management system that is the same as or similar to fleet management system **116**, a V2I system that is the same as or similar to V2I system **118**, and/or the like). A detailed description of convolution operations is included below with respect to FIG. **4**C.

In some embodiments, perception system **402** provides data associated with an input (referred to as an initial input) to first convolution layer **422** and perception system **402** generates data associated with an output using first convolution layer **422**. In some embodiments, perception system **402** provides an output generated by a convolution layer as input to a different convolution layer. For example, perception system **402** provides the output of first convolution layer **422** as input to sub-sampling layer **428**, second convolution layer **424**, and/or convolution layer **426**. In such an example, first convolution layer **422** is referred to as an upstream layer and sub-sampling layer **428**, second convolution layer **424**, and/or convolution layer **426** are referred to as downstream layers. Similarly, in some embodiments perception system **402** provides the output of sub-sampling layer **428** to second convolution layer **424** and/or convolution layer **426** and, in this example, sub-sampling layer **428** would be referred to as an upstream layer and second convolution layer **424** and/or convolution layer **426** would be referred to as downstream layers.

In some embodiments, perception system **402** processes the data associated with the input provided to CNN **420** before perception system **402** provides the input to CNN **420**. For example, perception system **402** processes the data associated with the input provided to CNN **420** based on perception system **420** normalizing sensor data (e.g., image data, LiDAR data, radar data, and/or the like).

In some embodiments, CNN **420** generates an output based on perception system **420** performing convolution operations associated with each convolution layer. In some examples, CNN **420** generates an output based on perception system **420** performing convolution operations associated with each convolution layer and an initial input. In some embodiments, perception system **402** generates the output and provides the output as fully connected layer **430**. In some examples, perception system **402** provides the output of convolution layer **426** as fully connected layer **430**, where fully connected layer **420** includes data associated with a plurality of feature values referred to as F1, F2 . . . . FN. In this example, the output of convolution layer **426** includes data associated with a plurality of output feature values that represent a prediction.

In some embodiments, perception system **402** identifies a prediction from among a plurality of predictions based on perception system **402** identifying a feature value that is associated with the highest likelihood of being the correct prediction from among the plurality of predictions. For example, where fully connected layer **430** includes feature values F1, F2, ... FN, and F1 is the greatest feature value, perception system **402** identifies the prediction associated with F1 as being the correct prediction from among the plurality of predictions. In some embodiments, perception system **402** trains CNN **420** to generate the prediction. In some examples, perception system **402** trains CNN **420** to generate the prediction based on perception system **402** providing training data associated with the prediction to CNN **420**.

Referring now to FIGS. **4**C and **4**D, illustrated is a diagram of example operation of CNN **440** by perception system **402**. In some embodiments, CNN **440** (e.g., one or more components of CNN **440**) is the same as, or similar to, CNN **420** (e.g., one or more components of CNN **420**) (see FIG. **4**B).

At step **450**, perception system **402** provides data associated with an image as input to CNN **440** (step **450**). For example, as illustrated, perception system **402** provides the data associated with the image to CNN **440**, where the image is a greyscale image represented as values stored in a two-dimensional (2D) array. In some embodiments, the data associated with the image may include data associated with a color image, the color image represented as values stored in a three-dimensional (3D) array. Additionally, or alternatively, the data associated with the image may include data associated with an infrared image, a radar image, and/or the like.

At step **455**, CNN **440** performs a first convolution function. For example, CNN **440** performs the first convolution function based on CNN **440** providing the values representing the image as input to one or more neurons (not explicitly illustrated) included in first convolution layer **442**. In this example, the values representing the image can correspond to values representing a region of the image (sometimes referred to as a receptive field). In some embodiments, each neuron is associated with a filter (not explicitly illustrated). A filter (sometimes referred to as a kernel) is representable as an array of values that corresponds in size to the values provided as input to the neuron. In one example, a filter may be configured to identify edges (e.g., horizontal lines, vertical lines, straight lines, and/or the like). In successive convolution layers, the filters associated with neurons may be configured to identify successively more complex patterns (e.g., arcs, objects, and/or the like).

In some embodiments, CNN **440** performs the first convolution function based on CNN **440** multiplying the values provided as input to each of the one or more neurons included in first convolution layer **442** with the values of the filter that corresponds to each of the one or more neurons. For example, CNN **440** can multiply the values provided as input to each of the one or more neurons included in first convolution layer **442** with the values of the filter that corresponds to each of the one or more neurons to generate a single value or an array of values as an output. In some embodiments, the collective output of the neurons of first convolution layer **442** is referred to as a convolved output. In some embodiments, where each neuron has the same filter, the convolved output is referred to as a feature map.

In some embodiments, CNN **440** provides the outputs of each neuron of first convolutional layer **442** to neurons of a downstream layer. For purposes of clarity, an upstream layer can be a layer that transmits data to a different layer (referred to as a downstream layer). For example, CNN **440** can provide the outputs of each neuron of first convolutional layer **442** to corresponding neurons of a subsampling layer. In an example, CNN **440** provides the outputs of each neuron of first convolutional layer **442** to corresponding neurons of first subsampling layer **444**. In some embodiments, CNN **440** adds a bias value to the aggregates of all the values provided to each neuron of the downstream layer. For example, CNN **440** adds a bias value to the aggregates of all the values provided to each neuron of first subsampling layer **444**. In such an example, CNN **440** determines a final value to provide to each neuron of first subsampling layer **444** based on the aggregates of all the values provided to each neuron and an activation function associated with each neuron of first subsampling layer **444**.

At step **460**, CNN **440** performs a first subsampling function. For example, CNN **440** can perform a first subsampling function based on CNN **440** providing the values output by first convolution layer **442** to corresponding neurons of first subsampling layer **444**. In some embodiments, CNN **440** performs the first subsampling function based on an aggregation function. In an example, CNN **440** performs the first subsampling function based on CNN **440** determining the maximum input among the values provided to a given neuron (referred to as a max pooling function). In another example, CNN **440** performs the first subsampling function based on CNN **440** determining the average input among the values provided to a given neuron (referred to as an average pooling function). In some embodiments, CNN **440** generates an output based on CNN **440** providing the values to each neuron of first subsampling layer **444**, the output sometimes referred to as a subsampled convolved output.

At step **465**, CNN **440** performs a second convolution function. In some embodiments, CNN **440** performs the second convolution function in a manner similar to how CNN **440** performed the first convolution function, described above. In some embodiments, CNN **440** performs the second convolution function based on CNN **440** providing the values output by first subsampling layer **444** as input to one or more neurons (not explicitly illustrated) included in second convolution layer **446**. In some embodiments, each neuron of second convolution layer **446** is associated with a filter, as described above. The filter(s) associated with second convolution layer **446** may be configured to identify more complex patterns than the filter associated with first convolution layer **442**, as described above.

In some embodiments, CNN **440** performs the second convolution function based on CNN **440** multiplying the values provided as input to each of the one or more neurons included in second convolution layer **446** with the values of the filter that corresponds to each of the one or more neurons. For example, CNN **440** can multiply the values provided as input to each of the one or more neurons included in second convolution layer **446** with the values of the filter that corresponds to each of the one or more neurons to generate a single value or an array of values as an output.

In some embodiments, CNN **440** provides the outputs of each neuron of second convolutional layer **446** to neurons of a downstream layer. For example, CNN **440** can provide the outputs of each neuron of first convolutional layer **442** to corresponding neurons of a subsampling layer. In an example, CNN **440** provides the outputs of each neuron of first convolutional layer **442** to corresponding neurons of second subsampling layer **448**. In some embodiments, CNN **440** adds a bias value to the aggregates of all the values provided to each neuron of the downstream layer. For example, CNN **440** adds a bias value to the aggregates of all the values provided to each neuron of second subsampling layer **448**. In such an example, CNN **440** determines a final value to provide to each neuron of second subsampling layer **448** based on the aggregates of all the values provided to each neuron and an activation function associated with each neuron of second subsampling layer **448**.

At step **470**, CNN **440** performs a second subsampling function. For example, CNN **440** can perform a second subsampling function based on CNN **440** providing the values output by second convolution layer **446** to corresponding neurons of second subsampling layer **448**. In some embodiments, CNN **440** performs the second subsampling function based on CNN **440** using an aggregation function. In an example, CNN **440** performs the first subsampling function based on CNN **440** determining the maximum input or an average input among the values provided to a given neuron, as described above. In some embodiments, CNN **440** generates an output based on CNN **440** providing the values to each neuron of second subsampling layer **448**.

At step **475**, CNN **440** provides the output of each neuron of second subsampling layer **448** to fully connected layers **449**. For example, CNN **440** provides the output of each neuron of second subsampling layer **448** to fully connected layers **449** to cause fully connected layers **449** to generate an output. In some embodiments, fully connected layers **449** are configured to generate an output associated with a prediction (sometimes referred to as a classification). The prediction may include an indication that an object included in the image provided as input to CNN **440** includes an object, a set of objects, and/or the like. In some embodiments, perception system **402** performs one or more operations and/or provides the data associated with the prediction to a different system, described herein.

Referring now to FIGS. **5A-8**, illustrated are diagrams of an implementation of a process for aligning a geodata map with a corresponding raster map in which the geodata map undergo a non-rigid transformation to maximize the coverage of the geodata map over the raster map.

With reference to FIG. **5A**, interactions for generating an updated geodata map are illustratively implemented by perception system **402**, which as noted above may be included within vehicle **102**. Additionally, or alternatively, the interactions for generating an updated geodata map may be performed by one or more of remote autonomous vehicle (AV) system **114**, fleet management system **116**, and V2I system **118**. The updated geodata map may be used, for example, to provide vehicle **102** with an improved understanding of the surrounding geographic area, thus enabling various systems (e.g., autonomous vehicle computer **202*f***) to perform functions such as planning of routes **106*b***, determining a location of the vehicle **102** within a geographic area, and/or the like.

The interactions of FIG. **5A** include passing, to an alignment engine **504**, a raster map **502*a*** and a geodata map **502*b*** associated with a geographic area. As described above, the raster map **502*a*** may correspond to one or more images of the geographic area (e.g., a raster map) from which a drivability mask identifying drivable surfaces can be derived. A distance map **513** may be generated at the vehicle **102**, for example, by the autonomous vehicle compute **400** (e.g., the "AV stack") or by one or more of remote systems such as remote autonomous vehicle (AV) system **114**, fleet management system **116**, and V2I system **118**. As shown in FIG. **5A**, the distance map **513** may be generated based on the raster map **502*a***, for example, by applying a distance transform operator to assign, to each pixel included in the raster map **502*a***, a label corresponding to a distance between the pixel and a closest obstacle.

Meanwhile, the geodata map **502*b*** may include graph-based geographic data (e.g., a geodata map from a geodata network) in which edges represent traffic lanes and nodes represent intersections between two or more traffic lanes. In some instances, the raster map **502*a*** may be overlapped with the geodata map **502*b*** to maximize a coverage of the geodata map **502*b*** over the raster map **502*a***. For example, as shown in FIG. **5A**, the distance map **513** and the geodata map **502*b*** may be input into the alignment engine **504** such that the alignment engine **504** may align, based on the distance map **513** and the geodata map **502*b***, the geodata map **502*b*** with the raster map **502*a***. To align the geodata map **502*b*** with the raster map **502*a***, the alignment engine **504** may perform a non-rigid transformation of the geodata map **502*b***, which may include deforming one or more nodes and edges in the geodata map **502***b*. In doing so, the alignment engine **504** may generate an updated geodata map **509** exhibiting maximum coverage over the raster map **502***a*.

Referring again to FIG. 5A, perception system **402** may also include an annotation engine **506** configured to generate, based at least on the updated geodata map **502***b*, one or more semantic labels identifying the physical features that are present in the corresponding geographic area. In some instances, the semantic annotation may be performed by a trained machine learning model, such as a neural network, in which case the updated geodata map **509** and the corresponding raster map **502***a* may be represented as set of aligned 2-dimensional matrixes, with each such matrix representing a layer of an image. For example, a color image may be represented in 3 channels, each of which corresponding to values of a respective primary color that, when combined, result in an image. A greyscale image may be represented as a single matrix, with values within the matrix representing the darkness of a pixel in the image.

In some embodiments, the annotation engine **506** may generate semantic labels based on the updated geodata map **509** at least because the non-rigid transformation applied to generate the updated geodata map **509** improves the accuracy and precision of localizing the physical features present in the raster map and the subsequent annotation of these physical features. To differentiate between different physical features, the alignment engine **504** may add, to the raster map **502***a* and/or geodata map **502***b*, one or more additional layers of information. For example, a first layer may be added to the raster map **502***a* to indicate whether each location in the matrix (e.g., each "pixel" in the raster map **502***a*) corresponds to an intersection (e.g., via concatenation of an image showing nodes in a graph of roads), a second layer may be added to indicate whether each location corresponds to a traffic lane (e.g., via concatenation of an image showing edges in the graph), a third layer may be added that indicates whether each location corresponds to a crosswalk, and/or the like.

FIG. 5B depicts a diagram illustrating an example of the raster map **502***a* and the corresponding distance map **513**. As shown, the raster map **502***a* may correspond to an image of a geographical area (e.g., a birds-eye view or top-view image of the geographic area). The distance map **513** may depict local maxima (e.g., brighter areas) that represent an ideal curve maximizing an overlap between, for example, the geodata map **502***b* and the raster map **502***a*. In some aspects, the distance map **513** may be generated by applying a distance transform operator (e.g., a Euclidean distance transform operator). In doing so, the distance map **513** may be generated to include, for each pixel of the raster map **502***a*, a label indicating a distance between the pixel and a closest obstacle. Based on the distance to the closest obstacle, the alignment engine **504** may calculate a local maxima representing an ideal curve maximizing an overlap between the geodata map **502***b* and the raster map **502***a*.

In some embodiments, the alignment engine **504** may define, based on a factor graph of the geodata map **502***b*, an error function. Aligning the geodata map **502***b* with the raster map **502***a* to ensure maximal coverage of the geodata map **502***b* over the raster map **502** may include minimizing the error function. For example, the error function may include a range error corresponding to a distance between one or more nodes in the geodata map **502***b* and one or more peaks in the distance map **513**. Furthermore, the error function may include a coverage error corresponding to an offset between the one or more edges in the geodata map **502***b* and one or more areas of local maxima on the distance map **513**. In some aspects, the error function may correspond to Equation (1) below.

$$x^* = \operatorname{argmin}_x F(x) \tag{1}$$

wherein x* denotes the optimal solution minimizing the minimization function $\operatorname{argmin}_x F(x)$.

The cost function F may correspond to Equation (2) below, in which $e_{i,j}^{r^T}\Omega_{i,j}^{r}e_{i,j}^{r}$ corresponds to the range error present across the geodata map **502***b* and $e_{i,j}^{c^T}\Omega_{i,j}^{c}e_{i,j}^{c}$ corresponds to the coverage error present across the geodata map **502***b*.

$$F = \sum_{(i,j)} \left(e_{i,j}^{r\,T} \Omega_{i,j}^{r} e_{i,j}^{r} + e_{i,j}^{c\,T} \Omega_{i,j}^{c} e_{i,j}^{c} \right) \tag{2}$$

wherein F denotes the cumulative error across range error e^r and coverage error e^c and Ω denotes an information matrix containing the values to weigh the alignment process. As noted, range error e^r corresponds to the difference between the length of an edge in the geodata map and the length of the same edge during alignment. The presence of a term corresponding to range error e^r in Equation (2) penalizes significant changes in the length of edges during alignment. Meanwhile, coverage error e^c measures how well an edge in the geodata map overlaps with the same edge in the corresponding raster map. Here, the presence of a term corresponding to coverage error e^c in Equation (2) penalizes large offsets between edges in the geodata map and one or more areas of local maxima on the distance map.

FIG. 5C depicts a diagram illustrating an example of a process for minimizing range error. In the example shown in FIG. 5C, an inner triangle **525** represents an optimal configuration of the geodata map **502***b* (e.g., the updated geodata map **509**) having a maximum coverage over the corresponding raster map **502***a*. The blurred triangle **530** represents the distance map **513** computed over the raster map **502***a*. An edge **520** with a first node **522***a* and a second node **522***b* may represent a current configuration of the geodata map **502***b*. At **540**, for example, the edge **520***a* is disposed over the left edge of the triangle **525**. In the example shown in FIG. 5C, the edge **520***a* does not fully cover the left edge of triangle **525** because the range of the edge **520***a* is below that of the left edge of the triangle **525**. In other cases, when the range of the edge **520***a* exceeds that of the left edge of the triangle **525**, the edge **520***a* may extend beyond the left edge of the triangle **525** at one or both ends. In some aspects, in order to reduce the range error for the edge **520***a*, the alignment engine **504** may increase the range of the edge **520***a* to achieve higher coverage over the left edge of the triangle **525**. For example, the alignment engine **504** may move the first node **522***a* and/or the second node **522***b* in order to deform the edge **520***a* and increase the coverage of the edge **520***a* over the triangle **525**. At **542**, an example of the deformation to minimize the range error associated with the edge **520***a* is shown where the first node **522***a* and/or the second node **522***b* are moved closer to the vertices of the triangle **525** in order to extend the edge **520***a* to cover the entire length of the left edge of the triangle **525**.

At **544**, the range of the edge **520***c* may be further extended by moving the first node **522***a* and/or the second node **522***b* closer to the vertices of the triangle **525** such that the first node **522***a* and the second node **522***b* substantially coincides with the vertices of the triangle **525** and the edge **520***c* covers all, or substantially all, of the left edge of the triangle **525**. Moving the first node **522***a* and/or the second node **522***b* in this manner to increase the range of the edge **520***c* may minimize the range error associated with the edge **520***c*. It should be appreciated that the same (or similar) operation may be performed for every node (and corresponding edge) present in the geodata map **502***b* in order to minimize the corresponding range error.

FIG. **5**D depicts a diagram illustrating an example of a process for minimizing coverage error. As noted above, coverage error may corresponding to an offset between the one or more edges in the geodata map **502***b* and one or more areas of local maxima on the distance map **513**. As shown in FIG. **5**D, the edge **520** may be modified to align the edge **520** with the left edge side of the triangle **525** by changing the position and/or orientation of the edge **520** relative to the left edge of the triangle **525** such that the edge **520** is positioned over the left edge of the triangle **525**.

At **550**, for example, the edge **520***a* may be disposed over the left edge of the triangle **525** but the orientation of the edge **520***a* is offset from that of the left edge of the triangle **525**. Thus, at **550**, the edge **520***a* does not cover the left side of triangle **525**. In some aspects, in order to reduce the coverage error associated with the edge **520***a*, the alignment engine **504** may adjust the orientation (and/or position) of the edge **520***a* to better coincide with that of the left edge of the triangle **525**. For example, at **552**, **554**, and **556**, the alignment engine **504** may rotate the edge **520***a* and shift the edge **520***a* downward such that the edge **520***a* is aligned with the left edge of the triangle **525**. Changing the position and/or the orientation of the edge **520***c* in this manner may minimize the coverage error associated with the edge **520***c*. It should be appreciated that the same (or similar) operation may be performed for edge present in the geodata map **502***b* in order to minimize the corresponding coverage error.

FIG. **6**A depicts an example of an initial geodata map. As shown, sections **602**, **604**, and **606** show areas of misalignment between the geodata map and a corresponding raster map. For example, at **602**, the geodata map includes a traffic path that overlaps with a curb or non-drivable surface of the raster map. FIG. **6**B depicts an example of an updated geodata map. As shown, in the updated geodata map, the traffic paths in the geodata map are aligned with the corresponding drivable surfaces in the raster map.

FIG. **7** is a diagram illustrating an example of a non-rigid transformation of a geodata map. In a rigid transformation process, the alignment engine **504** may merely move a raster map relative to the corresponding geodata map but the geodata map remains unchanged. However, a rigid transformation of the geodata map may not achieve maximal coverage between the geodata map and the raster map, and are therefore unsuitable for downstream tasks, such as annotation, localization, and navigation, that require precise alignment. Contrastingly, a non-rigid transformation of the geodata map may include deforming one or more nodes and/or edges in the geodata map to maximize coverage of the geodata map over the corresponding raster map. A non-rigid transformation of the geodata map may achieve higher coverage than a rigid transformation of the geodata map, and is applied in order to increase the accuracy and consistency of downstream tasks, such as annotation, navigation, and localization.

To further illustrate, FIG. **7** shows a close-up view of the section **602** of FIG. **6**A. As shown, section **602** includes an edge **720***a* in a region **1** having nodes **722***a* and **722***b* and an edge **720***b* having nodes **722***c* and **722***d* in a region **2**. Section **602** also includes an island **702***a*, an island **702***b*, and a curb **702***c*. In the example shown in FIG. **7**, the edge **720***b* intersects the curb **702***c* in the region denoted "2." In a rigid transformation, by moving down the raster map relative to the geodata map, it may be possible to recover the edge **720***b* coverage and avoid the intersection with the curb **702***c*. However, at the same time by moving the raster map relative to the geodata map, the edge **720***a* would also be affected and would lose coverage over a drivable surface on the raster map. Such artifacts are minimized by aligning the raster map and the geodata map through a non-rigid transformation of the geodata map.

FIG. **8** is a diagram **800** illustrating an example of a geodata map aligned with a raster map. As shown, the geodata map includes traffic lanes, which are represented as edges (e.g., edges **820**). The geodata map also includes intersections between two or more traffic lanes, which are represented as nodes (e.g., nodes **822**). As further shown, upon being aligned with the raster map through a non-rigid transformation, the edges and nodes of the geodata map may be aligned with the centers of drivable surface areas of the raster map (e.g., local maxima of the distance map).

Referring now to FIG. **9**, illustrated is a flowchart depicting an example of a process **900** for aligning a geodata map with a raster map. In some embodiments, one or more of the operations described with respect to process **900** are performed (e.g., completely, partially, and/or the like) by autonomous vehicle computer **400** of FIG. **4**A. Additionally, or alternatively, in some embodiments, one or more operations described with respect to process **900** are performed (e.g., completely, partially, and/or the like) by another device or group of devices separate from or including autonomous system **202** such as autonomous vehicle computer **202***f*.

In the example of FIG. **9**, the process **900** begins at block **902**, where the autonomous vehicle computer **400** obtains a raster map of a geographic area. In some aspects, the perception system **402** obtains the raster map. The raster map may include an image of the geographic area. For example, the image may be a birds-eye view (e.g., top-view) of the geographic area surrounding a vehicle **102**, a ground-level view from a camera on the vehicle **102**, a point cloud generated based on LiDAR sensors on the vehicle **102**, and/or the like.

At block **904**, the autonomous vehicle computer **400** generates a distance map corresponding to the raster map of the geographic area. For example, the distance map may be generated by at least applying, to the raster map of the geographic area, a distance transform operator such as a Euclidean distance transform operator. By applying the distance transform operator, each pixel in the raster map may be assigned a label corresponding to the distance between the pixel and a closest obstacle. In some aspects, a local maxima of the distance map may represent an ideal curve for aligning a geodata map with the raster map.

At block **906**, the autonomous vehicle computer **400** aligns the raster map with a geodata map of the geographic area. The aligning may include a non-rigid transformation of the geodata map in which the graph network of the geodata map is deformed to maximize a coverage of the geodata map over the raster map. For example, the geodata map may be deformed to minimize an error function determined based on a factor graph of the geodata map. The deforming of the geodata map may include moving one or more nodes of the geodata map to minimize a range error corresponding to a distance between the one or more nodes of the geodata map and one or more peaks in a distance map in which each pixel of the rater map is labeled with a distance from a closest obstacle. The moving of the one or more nodes may deform one or more corresponding edges in the geodata map. Moreover, the deforming of the geodata map may include moving one or more edges of the geodata map to minimize a coverage error corresponding to an offset between the one or more edges and one or more areas of local maxima on the distance map.

At block **908**, the autonomous vehicle computer **400** generates an updated geodata map of the geographic area. In some aspects, the updated geodata map provides a more accurate alignment of geographic data (e.g., the geodata map) with raster maps. The improved alignment may yield higher consistency during data retrieval to identify physical features in maps such as a road network, intersections, traffic lanes, road types, stores, crosswalks, or the like. The improved alignment may also facilitate more accurate generation of semantic annotations and basemaps.

In some aspects, the process **900** may further include generating one or more annotations identifying at least one physical feature present in the geographic area based on the updated geodata map. For example, the process **900** may include generating, based on the updated geodata map, one or more sematic labels identifying the physical features present in the geographic area. Semantic understanding may, in turn, enable a machine (e.g., the vehicle or one or more related systems) to process and interpret the geodata map and/or the corresponding raster map as a human might. Accordingly, semantic understanding represents a specific type of "computer vision"-a field of technology that attempts to enable computers to "see" the world in a manner similar to a human being. In some instances, the raster map may corresponding to an image of the geographic area around the vehicle (e.g., a birds-eye image, a street-level image, a point cloud image, and/or the like). Semantic annotations may designate certain portions of that image as representing one or more physical features present within the geographic area around the vehicle. For instance, an area in the image may be assigned a semantic label designating that area as a traffic lane (e.g., a drivable surface for motorized vehicles, for bikes, etc.), a crosswalk, an intersection, a traffic signal, a traffic sign, and/or the like.

Additionally, or alternatively, the process **900** may include generating a basemap of the geographic area based on the updated geodata map. As noted, the basemap of the geographic area may be a reference map upon which to overlay one or more layers of spatial data including, for example, roads, buildings, habitat types, administrative boundaries, and/or the like.

In the foregoing description, aspects and embodiments of the present disclosure have been described with reference to numerous specific details that can vary from implementation to implementation. Accordingly, the description and drawings are to be regarded in an illustrative rather than a restrictive sense. The sole and exclusive indicator of the scope of the invention, and what is intended by the applicants to be the scope of the invention, is the literal and equivalent scope of the set of claims that issue from this application, in the specific form in which such claims issue, including any subsequent correction. Any definitions expressly set forth herein for terms contained in such claims shall govern the meaning of such terms as used in the claims. In addition, when we use the term "further comprising," in the foregoing description or following claims, what follows this phrase can be an additional step or entity, or a sub-step/sub-entity of a previously-recited step or entity.

What is claimed is:

1. A method, comprising:

obtaining, using at least one processor, a raster map of a geographic area;

generating, using the at least one processor, a distance map corresponding to the raster map of the geographic area;

aligning, using the at least one processor, the raster map with a geodata map of the geographic area, wherein the aligning comprises deforming the geodata map relative to the distance map in order to maximize a coverage of the geodata map over the raster map; and

generating, using the at least one processor and based on the aligning, an updated geodata map of the geographic area.

2. The method of claim **1**, wherein the distance map is generated based on a distance transform operator.

3. The method of claim **1**, wherein the distance map is generated by labelling each pixel of the raster map with a distance from a closest obstacle.

4. The method of claim **1**, wherein the aligning the raster map with the geodata map comprises:

deforming the geodata map to minimize an error function that is determined based on a factor graph of the geodata map.

5. The method of claim **1**, wherein the aligning the raster map with the geodata map comprises:

moving one or more nodes of the geodata map to minimize a range error corresponding to a distance between the one or more nodes of the geodata map and one or more peaks in the distance map.

6. The method of claim **5**, further comprising:

moving of the one or more nodes by deforming one or more edges in the geodata map.

7. The method of claim **6**, wherein the aligning further includes moving the one or more edges of the geodata map to minimize a coverage error corresponding to an offset between the one or more edges and one or more areas of local maxima on the distance map.

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

generating one or more annotations identifying at least one physical feature present in the geographic area based on the updated geodata map.

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

generating a basemap of the geographic area based on the updated geodata map.

10. The method of claim **1**, wherein the geodata map comprises an image of the geographic area.

11. The method of claim **10**, wherein the image of the geographic area comprises one or more of a birds-eye view image, a ground-level image, or a point cloud image.

12. The method of claim **1**, wherein the geodata map comprises an electronic map data associated with a vector-based map of the geographic area.

13. A system, comprising:

at least one processor, and

at least one non-transitory storage media storing instructions that, when executed by the at least one processor, cause the at least one processor to at least:

obtain a raster map of a geographic area;

generate a distance map corresponding to the raster map of the geographic area;

align the raster map with a geodata map of the geographic area, the aligning comprising deforming the geodata map relative to the distance map in order to maximize a coverage of the geodata map over the raster map; and

generate, based on the aligning, an updated geodata map of the geographic area.

14. The system of claim **13**, wherein the distance map is generated based on a distance transform operator.

15. The system of claim 13, wherein the distance map is generated by labelling each pixel of the raster map with a distance from a closest obstacle.

16. The system of claim 13, wherein the instructions further cause at least one processor to at least:

deform the geodata map to minimize an error function that is determined based on a factor graph of the geodata map.

17. The system of claim 13, wherein the instructions further cause at least one processor to at least:

move one or more nodes of the geodata map to minimize a range error corresponding to a distance between the one or more nodes of the geodata map and one or more peaks in the distance map.

18. The system of claim 17, wherein the instructions further cause at least one processor to at least:

move the one or more nodes by deforming one or more edges in the geodata map.

19. The system of claim 13, wherein the instructions further cause at least one processor to at least:

move one or more one or more edges of the geodata map to minimize a coverage error corresponding to an offset between the one or more edges and one or more areas of local maxima on the distance map.

20. At least one non-transitory storage media storing instructions that, when executed by a computing system comprising a processor, cause the computing system to at least:

obtain a raster map of a geographic area;

generate a distance map corresponding to the raster map of the geographic area;

align the raster map with a geodata map of the geographic area, the aligning comprising deforming the geodata map relative to the distance map in order to maximize a coverage of the geodata map over the raster map; and

generate, based on the aligning, an updated geodata map of the geographic area.

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